Exhibit 6

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(80 pages)

Extension of sRGB color and GDI+

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Introduction

Color monitors, color scanners, and color printers are becoming the common equipments in companies, home offices, and homes. The color management among the different devices is important ever for the desktop publishing. The color standard sRGB was introduced to handle most of uses for non-publishers. Unlike CIE Lab or other color standard, sRGB has easier conversion rules for monitors and also it can be used as a color reference for the other types of devices. However, the conventional publishers use Pantone colors and CMYK values as a reference for printing. The demands for using those colors are still high for the high-end publishing and there is the criticism of sRGB in its narrow range of gamut. We must respond to those needs.

GDI+ has various features of gradient fills. When colors c1 and c2 are averaged, we expect to have the perceptually averaged color. However, sRGB has non-linearity produces the problems. Hence simple averaging of sRGB values does not produce the desired visual effects. Also GDI+ uses alpha channel for translucency. When the translucency is 50 %, simple multiplication of 0.5 to the sRGB value does not produce the 50 % translucent effects. We must linearize the sRGB value before we apply those operations to the color. When the linearized information is stored in 8 bit in each channel, we lose the accuracy of the original data in the lower values. Some contouring artifacts will appear and the resultant image does not look smooth.

We would like to solve the problems of narrow gamut and non-linearity of sRGB by proposing XsRGB format.

Extension of sRGB and Gamut

Figure 1. Extended sRGB space in CIE Diagram

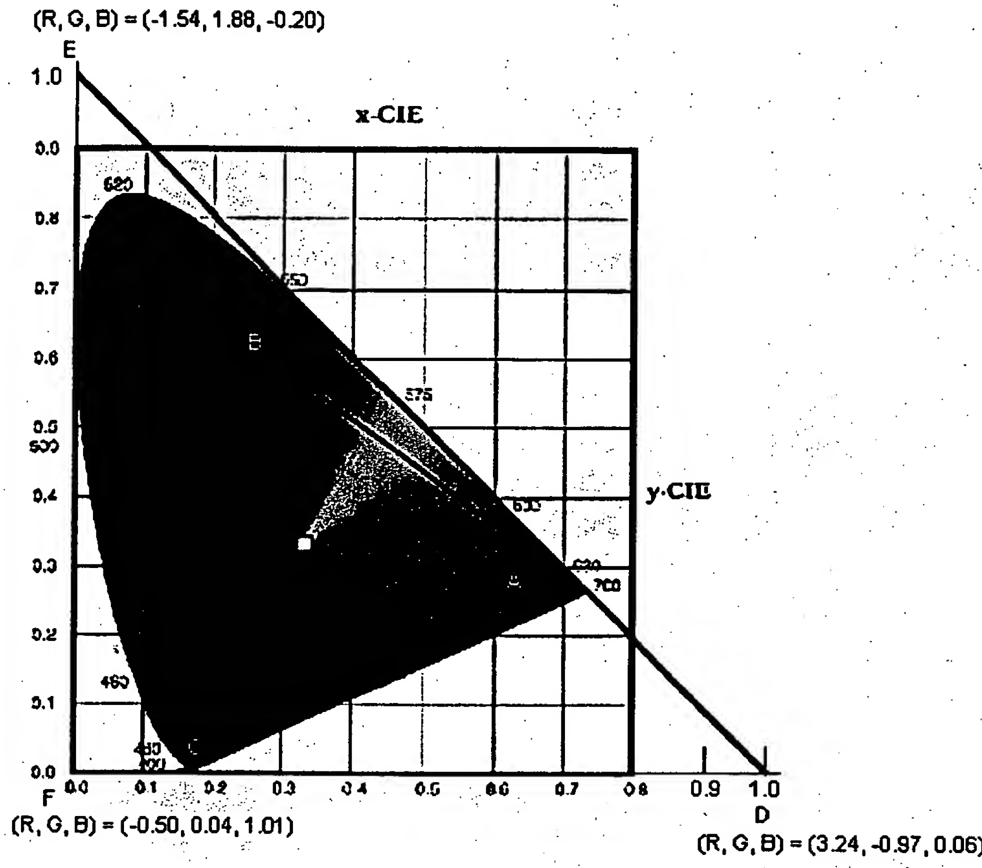

Figure 1 is a CIE chromaticity diagram. The points A, B, and C represent the red, green, and blue points in sRGB. Some printers go beyond sRGB gamut in cyan colors. One approach to extend the gamut is to use a laser display device as a color reference. It will cover most of the range. However, we need extra calculation to convert the laser device colors to the ordinary CRT colors (sRGB). Instead we can extend the range of sRGB beyond 1 and below 0. The ideal device can cover a triangle DEF in Figure 1. This corresponds to the linear sRGB values of (3.24, – 0.97, 0.06), (– 1.54, 1.88, – 0.20), and (– 0.50, 0.04, 1.01). If we want to express those values in 16-bit number, we must use 1.2.13 (1 bit for sign, 2 bit for integer, and 13 bit for decimals) format. This will cover each component within – 4 to 4.

Keeping the non-linear sRGB in 16-bit is problem. First of all, it is not clear how sRGB profile will be extended beyond 1 and below 0. Second, if we extend sRGB smoothly

(but linearly) beyond 1, the red value at point D reaches nearly 6. Hence, 1.2.13 format is not enough for non-linear sRGB.

I suggest that we always use the linear sRGB in 16-bit format. Each component can have 8192 levels of shades. The linear and non-linear conversion is accurate in that level. When we extend the range of RGB beyond 1 and below 0, the issue of the conversion between XsRGB and sRGB appear. We must discuss the conversion strategy and must have the standard methods among GDI+ team and ICM venders.

Color Support

GDI+'s architecture is based on sRGB and will be extended to XsRGB if the agreements are met between Microsoft GDI+ group and ICM venders. In addition to the color space, GDI+ uses alpha channel. Hence, GDI+ will have (X)sRGB + alpha for the basic color components. We interpret alpha as the coverage value of the pixel and its value is linearly scaled. Since ICM does not deal with alpha values, we do not modify alpha in any color format. "Color Support" here means conversions between (X)sRGB and different color format like CMYK, etc.

The first version of GDI+ APIs will be based on (X)sRGB. The future version will fully support ICM. So it is important to discuss the strategy of color conversion and color profile with venders. For a preliminary support, GDI+ may supply color conversion routines among various color spaces.

This is different from Java 2D. There are Color class and ColorSpace class in Java 2D. Color contains ColorSpace and Color itself could be CMYK or CIE Lab according to its ColorSpace. Each drawing primitives must be able to handle different color space. If we use this approach, GDI+ implementation will be very complicated. We must receive the feedback from printer venders if GDI+ need to have similar approach.

There are other issues in color space. One is the named color space. Offset printing venders may want to have Pantone color names. This can be integrated into GDI+ itself. For Pantone color images, we can introduce the index bitmaps that can contain the Pantone color names in addition to its (X)sRGB values or CMYK values. Image importer and image exporter can call a color converter if necessary. If a printer recognizes the color names, it can use them. If not, the pixel values in the color table is used in printing.

ICM and GDI+

ICM can convert one color space to another. The color spaces that ICM can transform are Gray, RGB, CMYK, XYZ, Yxy, Lab, etc. Other features of ICM is that it can read and create the color profiles. When we extend sRGB to XsRGB, the venders must agree

the XsRGB format and produce the profiles. The profile vender do not need to worry about the artificial gamut limitations imposed by sRGB.

If we leverage ICM codes or create wrapper to create ColorConverter class, GDI+ will satisfy the needs of color publishers as well as desktop publishers. The extension of ICM and its integration to GDI+ will bring the wide acceptance of GDI+ graphics among the color publishing industry.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

Technical Committee No.100: Audio, Video and Multimedia Systems and Equipment

Project Team 61966: Colour measurement and management in multimedia systems and equipment

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IEC/3WD 61966-2.1: Colour measurement and management in multimedia systems and equipment -

Part 2.1: Default RGB colour space - sRGB

This is the 3rd Working Draft prepared by co-project leader and confirmed by project leader. The document is based on

- 100/PT61966(Stokes)7A: 2nd Working Draft for IEC 61966-2.1
- 100/PT61966(PL)12: Report from the Scottsdale meeting on 1997-11-19
- Comments received after the Scottsdale meeting

As PT 61966 agreed in Scottsdale this document will be submitted to the Secretariat to be considered as committee draft for comments from national committees and liaison organizations.

During commenting period, the members of PT 61966 are requested to send their further comments, if any, either directly to project leader/co-project leader or to their respective national committees. Liaison officers are also request to forward this document and report the issue of this document to their organizations to receive comments.

All constructive comments received by PT 61966 will be properly dealt to revise this document.

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This document in PDF and relevant information is available at the URL,

http://w3.hike.te.chiba-u.ac.jp/IEC/100/PT61966
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

COLOUR MANAGEMENT IN MULTIMEDIA SYSTEMS – Part 2: Colour Management, Part 2.1: DEFAULT RGB COLOUR SPACE - sRGB

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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International Standard IEC 61966 has been prepared by project team 61966: Colour measurement and management in multimedia systems and equipment, of IEC technical committee TC100: Audio, Video and Multimedia Systems and Equipment.

The text of this standard is based on

FDIS	Report on voting
XXX/FDIS	XXX/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

INTERNATIONAL ELECTROTECHNICAL COMMISSION

COLOUR MANAGEMENT IN MULTIMEDIA SYSTEMS
- Part 2: Colour Management,
Part 2.1: DEFAULT RGB COLOUR SPACE – sRGB

1 GENERAL

1.1 Introduction

The method of digitisation in this part are designed to complement the current colour management strategies by enabling a method of handling colour in the operating systems, device drivers and the Internet that utilises a simple and robust device independent colour definition. This will provide good quality and backward compatibility with minimum transmission and system overhead. Based on a calibrated colorimetric RGB colour space well suited to cathode ray tube (CRT) displays, flat panel displays, television, scanners, digital cameras, and printing systems, such a space can be supported with minimum cost to software and hardware vendors. The intent is to promote its adoption by showing the benefits of supporting a standard colour space, and the suitability of this standard colour space, sRGB.

Recently the International Colour Consortium has proposed breakthrough solutions to problems in communicating colour in open systems. Yet the ICC profile format does not provide a complete solution for all situations.

Currently, the ICC has one means of tracking and ensuring that a colour is correctly mapped from the input to the output colour space. This is done by attaching a profile for the input colour space to the image in question. This is appropriate for high end users. However, there are a broad range of users that do not require this level of flexibility and control in an embedded profile mechanism. Instead it is possible to create a single, standard default colour space definition that can be processed as an implicit ICC sRGB profile. Additionally, most existing file formats do not, and may never, support colour profile embedding, and finally, there are a broad range of uses that actually discourage people from appending any extra data to their files. A common standard RGB colour space addresses these issues and is useful and necessary. This approach maintains the advantage of a clear relationship with ICC colour management systems while minimising software processes and support requirements.

Application developers and users who do not want the overhead of embedding profiles with documents or images should convert them to a common colour space for storage. Currently there is a plethora of RGB CRT-based colour spaces attempting to fill this void with little guidance or attempts at standardisation. There is a need to merge the many standard and non-standard RGB display spaces into a single standard RGB colour space. This standard dramatically improves the colour fidelity in the desktop environment by meeting this need. For example, if operating system vendors provide support for a this standard RGB colour space, the input and output device vendors that support this standard colour space could easily and confidently communicate colour without further colour management overhead in the most common situations. The three major factors of this RGB space are the colorimetric RGB definition, the simple exponent value of 2.2, and the well-defined viewing conditions, along with a number of secondary details necessary to enable the clear and unambiguous communication of colour.

The dichotomy between the device dependent (e.g. amounts of ink expressed in CMYK or digitised video voltages expressed in RGB) and device independent colour spaces (such as CIELAB or CIEXYZ) has created a performance burden on applications that have attempted to avoid device colour spaces. This is primarily due to the complexity of the colour transforms they need to perform to return the colours to device dependent colour spaces. This situation is

worsened by a reliability gap between the complexity and variety of the transforms, making it hard to ensure that the system is properly configured.

This standard addresses these concerns, serves the needs of PC and Web based colour imaging systems is based on the average performance of personal computer displays. This solution is supported by the following observations:

- Most computer displays are similar in their key colour characteristics — the phosphor chromaticities (primaries) and transfer function
- RGB spaces are native to displays, scanners and digital cameras, which are the devices with the highest performance constraints
- RGB spaces can be made device independent in a straightforward way. They can also describe colour gamuts that are large enough for all but a small number of applications.

This combination of factors makes a colorimetric RGB space well suited for wide adoption since it can both describe the colours in an unambiguous way and be the native space for actual hardware devices. This, many readers will recognise, describes in a roundabout way what has been the practice in colour television for some 45 years. This proven methodology provides excellent performance where it is needed the most, the rapid display of images in CRT displays.

There are two parts to the proposed standard described in this standard: the encoding transformations and the reference conditions. The encoding transformations provide all of the necessary information to encode an image for optimum display in the reference conditions. If actual conditions differ from reference conditions, additional rendering transformations may be required.

1.2 Scope

The IEC 61966 standards are a series of methods and parameters for colour measurements and management for use in multimedia systems and equipment applicable to the assessment of colour reproduction.

This part of IEC 61966 is applicable to the encoding and communication of RGB colours used in computer systems and similar applications by defining encoding transformations for use in defined reference conditions. The encoding transformations are the default RGB colour definition when no other colour space information is available or appropriate.

If actual conditions differ from the reference conditions, additional rendering transformations could be required. Such additional rendering transformations are beyond the scope of this standard.

1.3 Normative References

The following normative documents contain provisions, which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards

IEC 60050(845): 1987, *International Electrotechnical Vocabulary (IEV) - Chapter 845: Lighting*

CIE 15.2: 1986, Colorimetry (2nd Ed.)

CIE 122: 1996, *The relationship between digital and colorimetric data for computer-controlled CRT displays*

ITU-R BT.709-2: 1995, *Parameter Values for the HDTV Standards for Production and International Programme Exchange*

ISO 3664: 1975, *Photography – Illumination conditions for viewing colour transparencies and their reproduction*

ISO 9358:1994, Optics and optical instruments -- Veiling glare of image forming systems -- Definitions and methods of measurement

1.4 Definitions

For the purpose of this International Standard, the following definitions apply. Definitions of illuminance, luminance, tristimulus, and other relating lighting terms are defined in reference IEC 60050(845) International Electrotechnical Vocabulary (IEV) - Chapter 845 Lighting. Veiling glare is defined in reference ISO 9358:1994.

1.4.1
ambient illuminance level
The illuminance level due to lighting in the viewing environment not from the display measured normal from the display faceplate at a typical viewing distance.

1.4.2
ambient white point
The coordicate poitn in the CIE 1931 XYZ colour space defined by CIE 15.2 due to lighting in the viewing environment, not from the display measured normal from the display faceplate relative to a perfect reflecting diffuser.

1.4.3
display illuminant white point
The point in the xy chromaticity diagram defined by CIE 15.2 when the red, green and blue channels are at 100 % as measured normal from the display faceplate relative to a perfect reflecting diffuser.

1.4.4
display background
The environment of the colour element extending typically for about ten degrees from the edge of the proximal field in all, or most directions. When the proximal field is the same colour as the background, the latter is regarded as extending from the edge of the colour element considered.

1.4.5
display model offset
The display model offset measured consistently with CIE 122, representing the black offset level of the display grid voltage.

1.4.6
display gun/phosphor gamma
The transfer characteristic relating the input signal data and the output luminance as represented by an exponential function. This transfer characteristic represents the intrinsic characteristics of the CRT display grid voltage and electron beam current acting on the display phosphors.

1.4.7
display luminance level
The luminance level of the display measured consistently with CIE 122.

1.4.8
display surround
The field outside the background, filling the field of vision.

1.4.9
display proximal field
The immediate environment of the colour element considered, extending typically for about two degrees from the edge of the colour element considered in all or most directions.

1.4.10
World Wide Web
The universe of network-accessible information, the embodiment of human knowledge. The Web has a body of software, and a set of protocols and conventions. Through the use hypertext and multimedia techniques, the web is easy for anyone to roam, browse, and contribute to.

2 REFERENCE CONDITIONS

2.1 Reference Display Conditions

1. Display luminance level — 80 cd/m2
2. Display white point — x = 0,3127, y = 0,3291 (D65)
3. Display model Offset (R,G and B) — 0,055
4. Display Gun/Phosphor Gamma (R, G, and B) — 2,4

The CIE chromaticities for the red, green, and blue ITU-R BT.709-2 reference primaries, and for CIE Standard Illuminant D65, are given in table 1.

Table 1 CIE chromaticities for ITU-R BT.709 reference primaries and CIE standard illuminant

	Red	Green	Blue	D65
X	0,6400	0,3000	0,1500	0,3127
Y	0,3300	0,6000	0,0600	0,3291
Z	0,0300	0,1000	0,7900	0,3583

The reference display characterisation is based on the CIE 122 display characterisation standard. Relative to this standard methodology, the reference display is characterised by the equation below.

$$V_{sRGB} = \left[{(V'_{sRGB} + 0{,}055)}/{1{,}055} \right]^{2,4} \qquad (1)$$

2.2 Reference Viewing Conditions

Specifications for the reference viewing environments are based on ISO 3664 and are defined as follows:

1. Reference Background — for the background as part of the display screen, the background is 20 % of the reference display luminance level
2. Reference Surround — 20 % reflectance of the reference ambient illuminance level

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3. Reference Proximal Field	20 % of the reflectance of the reference display luminance level
4. Reference Ambient Illuminance Level	64 lx
5. Reference Ambient White Point	x = 0,3457, y = 0,3585 (D50)
6. Reference Veiling glare	1,0 %

2.3 Reference Observer Conditions

The reference observer is the CIE 1931 two-degree standard observer from CIE 15.2.

3 ENCODING CHARACTERISTICS

3.1 Introduction

The encoding transformations between 1931 CIEXYZ values and 8 bit RGB values provide unambiguous methods to represent optimum image colorimetry when viewed on the reference display in the reference viewing conditions by the reference observer. The 1931 CIEXYZ values are scaled from 0,0 to 1,0, not 0,0 to 100,0. These non-linear sR'G'B' values represent the appearance of the image as displayed on the reference monitor in reference viewing environment. The sRGB tristimulus values are linear combinations of the 1931 CIE XYZ values as measured on the faceplate of the display, which assumes the absence of any significant veiling glare. Recommended treatments for both veiling glare and viewing conditions are provided in Annexes G and H.

3.2 Transformation from RGB values to 1931 CIE XYZ values

The relationship is defined as follows:

$$\begin{aligned} R'_{sRGB} &= R_{8bit} \div 255{,}0 \\ G'_{sRGB} &= G_{8bit} \div 255{,}0 \\ B'_{sRGB} &= B_{8bit} \div 255{,}0 \end{aligned} \qquad (2)$$

If $R'_{sRGB}, G'_{sRGB}, B'_{sRGB} \leq 0{,}03928$

$$\begin{aligned} R_{sRGB} &= R'_{sRGB} \div 12{,}92 \\ G_{sRGB} &= G'_{sRGB} \div 12{,}92 \\ B_{sRGB} &= B'_{sRGB} \div 12{,}92 \end{aligned} \qquad (3)$$

else $R'_{sRGB}, G'_{sRGB}, B'_{sRGB} > 0{,}03928$

$$\begin{aligned} R_{sRGB} &= \left[(R'_{sRGB} + 0{,}055) / 1{,}055 \right]^{2,4} \\ G_{sRGB} &= \left[(R'_{sRGB} + 0{,}055) / 1{,}055 \right]^{2,4} \\ B_{sRGB} &= \left[(R'_{sRGB} + 0{,}055) / 1{,}055 \right]^{2,4} \end{aligned} \qquad (4)$$

and

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$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0{,}4124 & 0{,}3576 & 0{,}1805 \\ 0{,}2126 & 0{,}7152 & 0{,}0722 \\ 0{,}0193 & 0{,}1192 & 0{,}9505 \end{bmatrix} \begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} \qquad (5).$$

The above equations closely fit a simple power function with an exponent of 2,2. This maintains consistency with the legacy of desktop and video images.

3.3 Transformation from 1931 CIE XYZ values to RGB values

The sRGB tristimulus values can be computed using the following relationship:

$$\begin{bmatrix} R_{sRGB} \\ G_{sRGB} \\ B_{sRGB} \end{bmatrix} = \begin{bmatrix} 3{,}2410 & -1{,}5374 & -0{,}4986 \\ -0{,}9692 & 1{,}8760 & 0{,}0416 \\ 0{,}0556 & -0{,}2040 & 1{,}0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (6)$$

In the RGB encoding process, negative sRGB tristimulus values, and sRGB tristimulus values greater than 1,00 are not retained. When encoding software cannot support this extended range, the luminance dynamic range and colour gamut of RGB is limited to the tristimulus values between 0,0 and 1,0 by simple clipping.

The sRGB tristimulus values are transformed to non-linear sR'G'B' values as follows:

If $R_{sRGB}, G_{sRGB}, B_{sRGB} \leq 0{,}00304$

$$\begin{aligned} R'_{sRGB} &= 12{,}92 \times R_{sRGB} \\ G'_{sRGB} &= 12{,}92 \times G_{sRGB} \\ B'_{sRGB} &= 12{,}92 \times B_{sRGB} \end{aligned} \qquad (7)$$

else $R_{sRGB}, G_{sRGB}, B_{sRGB} > 0{,}00304$

$$\begin{aligned} R'_{sRGB} &= 1{,}055 \times R_{sRGB}{}^{(1{,}0/2{,}4)} - 0{,}055 \\ G'_{sRGB} &= 1{,}055 \times G_{sRGB}{}^{(1{,}0/2{,}4)} - 0{,}055 \\ B'_{sRGB} &= 1{,}055 \times B_{sRGB}{}^{(1{,}0/2{,}4)} - 0{,}055 \end{aligned} \qquad (8)$$

The non-linear sR'G'B' values are converted to digital code values. This conversion scales the above sR'G'B' values by using the equation below where WDC represents the white digital count and KDC represents the black digital count.

$$\begin{aligned} R_{8bit} &= \left((WDC - KDC) \times R'_{sRGB}\right) + KDC \\ G_{8bit} &= \left((WDC - KDC) \times G'_{sRGB}\right) + KDC \\ B_{8bit} &= \left((WDC - KDC) \times B'_{sRGB}\right) + KDC \end{aligned} \qquad (9)$$

This standard specified a black digital count of 0 and a white digital count of 255 for 24-bit (8-bits/channel) encoding. The resulting RGB values are formed according to the following equations:

$$
\begin{aligned}
R_{8bit} &= ((255{,}0 - 0{,}0) \times R'_{sRGB}) + 0{,}0 \\
G_{8bit} &= ((255{,}0 - 0{,}0) \times G'_{sRGB}) + 0{,}0 \\
B_{8bit} &= ((255{,}0 - 0{,}0) \times B'_{sRGB}) + 0{,}0
\end{aligned} \tag{10}
$$

This is simplified as shown below:

$$
\begin{aligned}
R_{8bit} &= 255{,}0 \times R'_{sRGB} \\
G_{8bit} &= 255{,}0 \times G'_{sRGB} \\
B_{8bit} &= 255{,}0 \times B'_{sRGB}
\end{aligned} \tag{11}
$$

ANNEX A
(informative)
Ambiguity in the Definition of the Term "Gamma"

Historically, both the photographic and television industries claim integral use of the term "gamma" for different effects. Hurter and Driffield first used the term in the 1890's in describing the straight-line portion of the density vs. log exposure curves that describe photographic sensitometry. The photographic sensitometry field has used several interrelated terms to describe similar effects, including; gamma, slope, gradient, and contrast. Both Languimier in the 1910's and Oliver in the 1940's defined "gamma" for the television industry (and thus the computer graphics industry) as the exponential value in both simple and complex power functions that describe the relationship between gun voltage and intensity (or luminance). In fact, even within the television industry, there are multiple, conflicting definitions of "gamma." These include differences in describing physical aspects (such as gun "gamma" and phosphor "gamma"). These also include differences in equations for the same physical aspect (there are currently at least three commonly used equations in the computer graphics industry to describe the relationship between gun voltage and intensity, all of which provide significantly different results). After significant insightful feedback from many industries, this standard has chosen to explicitly avoid the use of the term "gamma." Furthermore, it appears that the usefulness as an unambiguous, constructive standard terminology is impossible and its continued use is detrimental to cross standard and unambiguous communication.

Annex B
(informative)
sRGB and ITU-R BT.709-2 Compatibility

The compatibility between this standard and the ITU-R BT.709-2 was a primary consideration in development of this standard. Unfortunately, ITU-R BT.709-2 can be somewhat confusing. This annex is an attempt to clarify and reduce this confusion.

In April 1990 unanimous worldwide agreement on a calibrated non-linear RGB space for HDTV production and program exchange in ITU-R BT.709-2 was obtained. This recommendation specifies the encoding of real world scene tristimulus values into a reference display RGB colour space assuming a dark viewing condition. The ITU specification is rather vague on defining the reference display. This standard provides a clear and well-defined reference display for ITU-R BT.709-2 for a dim viewing environment.

ITU-R BT.709-2 specifically describes the encoding transfer function for a video camera that when viewed on a "standard" display will produce excellent image quality. The implicit target of this encoding is a standard video display whose transfer function is *not* explicitly delineated. Instead a typical display setup is assumed. This paper attempts to explicitly describe a standard display characterisation that is compatible with ITU-R BT.709-2.

This is illustrated in figures B.1-B.3 below. Figure B.1 is directly derived from ITU-R BT.709-2. This standard provides mathematical methods to transform from tristimulus values of the scene using a video camera into a reference display device space.

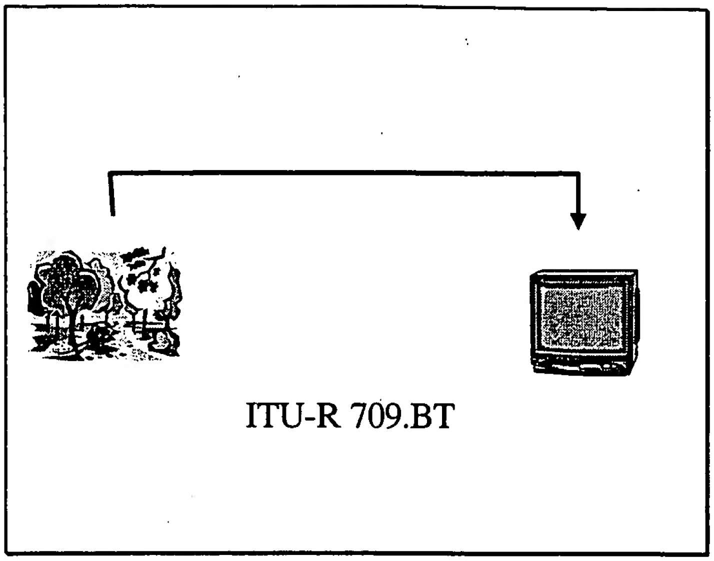

Figure B.1

Figure B.2 expands the implicit step of these methods and shows the transformation between the original scene tristimulus values into the target display tristimulus values. Since these two viewing conditions are different, an implicit compensation is made to account for these differences (i.e. veiling glare, surround and ambient illuminance). In order to provide an independent display reference colour space, the reference display, viewing conditions and observer implicit in the encoding transforms must be extracted from this confounded compensation. This is precisely the goal of this standard.

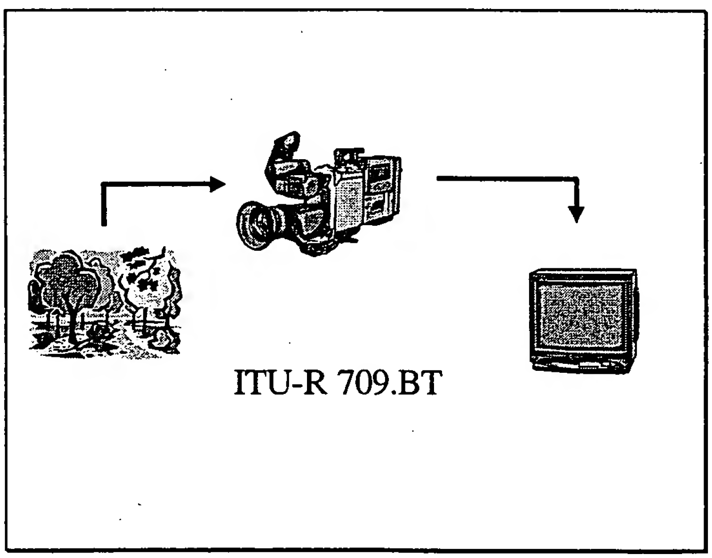

Figure B.2

Figure B.3 illustrates both the sRGB colour space and the extraction of the reference display specifications (with its viewing conditions) implicit within ITU-R BT.709-2. By building on this system, the sRGB colour space provides a display definition that can be used independently from ITU-R BT.709-2 while maintaining compatibility.

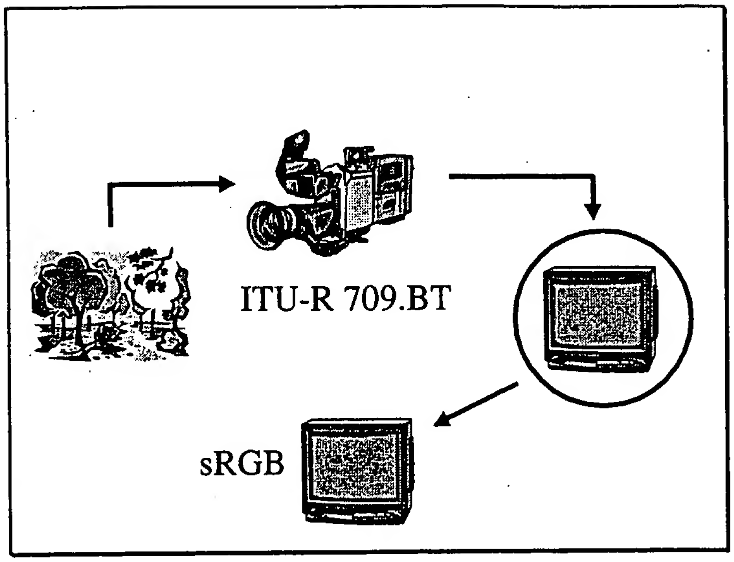

Figure B.3

This sRGB recommendation essentially defines the second part of this transformation between the reference RGB display space and the display CIEXYZ tristimulus values in a dim viewing environment.

Annex C
(informative)
Usage Guidelines

C.1 Definition of a Colour Space

For colour to be reproduced in a predictable manner across different devices and materials, it has to be described in a way that is independent of the specific behaviour of the mechanisms and materials used to produce it. For instance, colour displays and colour printers use very different mechanisms for producing colour. To address this issue, current methods require that colour be described using device independent colour co-ordinates, which are translated into device dependent colour co-ordinates for each device.

C.2 Definition of Colour Management:

Traditionally, operating systems have supported colour by declaring support for a particular colour space, RGB in most cases. However, since RGB varies between devices, colour was not reliably reproduced across different devices.

The high-end publishing market could not meet its needs with the traditional means of colour support, so the various OS's added support for using International Colour Consortium (ICC) profiles to characterise device dependent colours in a device independent way. They use the profiles of the input device that created an image and the output device that displayed the image and create a transform that moves the image from the input device's colour space to the output device's colour space. This resulted in very accurate colour. However, it also involved the overhead of transporting the input device's profile with the image and running the image through the transform.

This standard provides an additional means of managing colour that is optimised to meet the needs of most users without the overhead of carrying an ICC profile with the image: the addition to the OS and the Internet of support for a Standard Colour Space. Since the image is in a known colour space and the profile for that colour space would ship with the OS and display application, this enables the end users to enjoy the benefits of colour management without the overhead of larger files. While it may be argued that profiles could buy slightly higher colour accuracy, the benefits of using a standard colour space far out-weigh the drawbacks for a wide range of users. The migration of devices to natively support the standard colour space will further enhance the speed and quality of the user experience.

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It is recommended to use the colour space, sRGB, that is consistent with but is a more tightly defined derivative of ITU-R BT.709-2 as the standard colour space for the OS's and the Internet. In April of 1990 this space obtained unanimous worldwide agreement as the calibrated non-linear RGB space for HDTV production and program exchange.

C.3 Specifying Colour of Page Elements

Complex documents are often composed of multiple page elements of graphics, text and images. These elements may be in different colour spaces. It is recommended that all page elements be assumed to be in the sRGB colour space unless embedded ICC profiles (or other explicit methods) indicate otherwise. The relationship between sRGB and ICC profiles is shown in table C.1 below.

Table C.1 Relationship between sRGB and ICC Profiles

ICC and sRGB	ICC Source Profile	No ICC Source Profile
ICC Destination Profile	ICC Source ICC Destination	sRGB Source ICC Destination
No ICC Destination Profile	ICC Source sRGB Destination	sRGB Source sRGB Destination

C.4 Standard Colour Space in Practice

Once page elements are converted to sRGB, the display application should interpret the colour space correctly and use the OS colour management to image the page. Table C.2 below summarises how the display application handles colour management in each of the possible scenarios.

Table C.2 How a Display Application Handles Colour Management

	Page Element Colours (sRGB)	Page with no Colour Space information	Re-purpose Data outside of Display application environment
Embedded Profile in Image	Colour Space for Image determined by embedded profile.	Colour Space for Image determined by embedded profile.	Colour Space for Image determined by embedded profile.
Image file specifies sRGB	Colour Space for Image is sRGB	Colour Space for Image is sRGB	Colour Space for Image is sRGB
Image has no Colour space information.	Colour Space for Image is sRGB	Colour Space for image is sRGB.	Colour Space for image is sRGB.
Text	Colour Space for text is sRGB	Colour Space for text is sRGB.	Colour Space for text is sRGB.
Graphics	Colour Space for Graphics is sRGB	Colour Space for graphics is sRGB.	Colour Space for graphics is sRGB.

C.5 Display Application Scenarios

The following cases describe what an end-user sees in the various scenarios:

C5.1 Image not in sRGB, does not have an embedded ICC profile, and no display/output device ICC profile

This is the behaviour before colour management systems were added. Even though the image is assumed to be in sRGB colour space, it is imaged (displayed, printed etc.) without translation to the device colour space since the output profile is not available. The quality varies tremendously since output device characteristics differ greatly.

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C5.2 Image not in sRGB, does not have an embedded ICC profile, and system has a display/output device ICC profile

Since the image has no ICC profile, it is assumed to be in the sRGB colour space. In this scenario, the resulting image will be consistent across devices; however it could be different from the original image.

C5.3 Image in sRGB, and no display/output device ICC profile

In this scenario, the image has been run through a transform that consists of the input device ICC profile, and the sRGB ICC profile, or it was created using devices that conform to sRGB. However, since the system has no ICC profile for the output device, it will simply assume the image is in the device's colour space. If all the images rendered on the output device are in sRGB, then they will at least be consistent with respect to each other on a given display/output device.

C5.4 Image in sRGB, and system has a display/output device ICC profile

In this scenario, the image has been run through a transform that consists of the input device ICC profile, and the sRGB ICC profile, or it was created using devices that conform to sRGB. Because the system has an ICC profile for the output device, the image can be converted to the output device's colour space and imaged. The resulting image will be consistent across devices, and will be very close to the original in appearance.

C5.5 Image in sRGB, and display/output device is sRGB compliant

In this scenario, the image has been run through a transform that consists of the input device ICC profile, and the sRGB ICC profile, or it was created using devices that conform to sRGB. As the output device has been designed to conform to sRGB, and is associated with that ICC profile, a transform is not necessary for this case. The OS realises that no transformation is required and simply images the image directly on the output device. This case is ideal since there is no colour transformation at output time, and the image is more compact since there is no ICC profile embedded in it. The resulting image will be consistent across devices, and will be very close to the original in appearance.

C5.6 Image not in sRGB, has an embedded ICC profile, and no display/output device ICC profile

The decision to save the image in a device specific colour space and embed an ICC profile should result in equal or higher quality than saving the image in sRGB. Since the device specific colour space will not display correctly on an unknown output device, it will be transformed into sRGB, using the embedded ICC profile as the source profile and sRGB as the destination profile.

C5.7 Image not in sRGB, has an embedded ICC profile, and system has a display/output device ICC profile

This is the standard colour management scenario. The two ICC profiles are combined to produce a transform that will map the colours of the image into the output device's colour space. The resulting image will be consistent across devices, and will be very close to the original in appearance.

C.6 Authoring Scenarios

The following scenarios describe how to get an image into the sRGB colour space when creating it.

C6.1 Image created on a device that has no ICC profiles and is not sRGB compliant

Display the image on a display that is sRGB compliant or that has an ICC profile. Edit the image until it looks good on the display. For displays that are not sRGB compliant but have ICC

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profiles, depending on the capabilities of the application, either use the application to save the image as sRGB or embed the display's profile into the image, and use a tool to create a transform with the display's profile and the sRGB profile and run the image through the transform. If the image file format supports it, specify the image is in sRGB.

C6.2 Image created on a device that has ICC profiles and is not sRGB compliant

Use a tool to create a transform with device's profile and the sRGB profile. Then run the image through the transform, specify the image is in sRGB if the image file format supports it.

C6.3 Image created on a device that is sRGB compliant

Specify the image is in sRGB if the image file format supports this.

C.7 Palette Issues

There are several different scenarios to consider when dealing with palletised images and displays.

C7.1 Image does not have a colour table (> 8 bpp), and client graphics subsystem is not palletised

The image is run through a colour management transform as described in the previous section, and the resulting 24 bpp image is displayed on the display.

C7.2 Image has a colour table (8 bpp) and client display is not palletised

The colour table accompanying the image is run through a colour management transform, and the resulting colour table is used with the image for display. The displayed image is very close to original image.

C7.3 Image does not have a colour table (>8 bpp) and client display is palletised.

The software displaying the image (e.g. display application) should use the default palette that is defined in sRGB space, convert it into device colour space by running it through a colour management transform, and use this palette to display the image. The resulting image gets dithered into the closest possible colours on the display. The assumption is that the display profile is created with the default palette selected.

C7.4 Image has a colour table (8 bpp) and was created using the default palette and client display is palletised

The software displaying the image should follow the same steps as above. The resulting image is very close to the original image and unintentional dithering is eliminated. If the original image only had colours in the default palette, the final image doesn't have any dithering.

C7.5 Image has a colour table (8 bpp) and was created using an arbitrary palette and client display is palletised

If the client display only has a palletised profile and can only display the image by discarding this profiled palette and replacing it with an uncalibrated palette, it is not recommended to colour manage this scenario. If the client display is able to treat the image as if it was a truecolour (unpalettised) image, it should proceed as for case 3 above.

Note that cases 3 and 4 assume an industry standard default palette defined in sRGB colour space that will be used by authoring and display software to handle 8bpp images.

Annex D
(informative)
Typical Viewing Conditions

While office desktop would theoretically use the viewing conditions which represent the actual or typical office viewing environment, if this is done with 24 bit images a significant loss in the quality of shadow detail results. This is due to the typical viewing veiling glare of approximately 5 percent into a 24 bit image as opposed to the reference viewing veiling glare of 1 percent. This is somewhat compensated for by the apparent visual darkening effect of the lighter surround. It is therefore recommended to use the reference viewing environment for most situations including when one's viewing environment is consistent with the typical viewing environment and not the reference viewing environment.

1. Typical Ambient Illuminance Level	200 lx
2. Typical Ambient White Point	$x = 0,3457$, $y = 0,3585$ (D50)
3. Typical Viewing Veiling glare	5,0 %

The *typical ambient illuminance level* is intended to be representative of a typical office viewing environment. Note that the illuminance is at least an order of magnitude lower than average outdoor levels.

The chromaticities of the *typical ambient white* are those of CIE D_{50}.

Typical Viewing veiling glare is specified to be 5 % of the maximum white-luminance level.

Annex E
(informative)
Recommended Treatment for Viewing Conditions

Colour appearance on a CRT display is significantly affected by the ambient lighting, since the human visual system changes its sensitivity according to the viewing conditions. At its meeting held in Kyoto in May 1997, CIE Technical Committee TC 1-34 agreed to adopt as the simple version the colour appearance model CIECAM97s. While the inclusion of the year 97 in the designation is intended to indicate the interim nature of the model, this same caveat is providing for the CIELAB and CIELUV colour spaces which are ubiquitous in colour reproduction work today and should not be discourage the use of this model. Still it is due to the newness of this recommendation that this model is a recommendation and not a requirement for compliance with this standard. In order to use this standard in viewing conditions that are not compliant with the reference conditions, it is therefore strongly recommended that the CIECAM97s colour appearance model be used to transform into and out of the reference viewing conditions.

Unfortunately, the CIECAM97s colour appearance model does not account for two important aspects of viewing conditions; veiling glare and black mapping.

The recommended veiling glare compensation is shown below. Equation 12 should be applied after equation 5 to provide input into the CIECAM97s model.

$$\begin{aligned} X_{CRT} &= X_{xRGB} + VG \times X_{ambient} \\ Y_{CRT} &= Y_{xRGB} + VG \times Y_{ambient} \\ Z_{CRT} &= Z_{xRGB} + VG \times Z_{ambient} \end{aligned} \qquad (12)$$

Equation 13 should be applied before equation 6 and after the CIECAM97s model.

$$\begin{aligned} X_{sRGB} &= X_{CRT} - VG \times X_{ambient} \\ Y_{sRGB} &= Y_{CRT} - VG \times Y_{ambient} \\ Z_{sRGB} &= Z_{CRT} - VG \times Z_{ambient} \end{aligned} \qquad (13)$$

Finally, it is strongly recommended to rescale the lightness dimension of the CIECAM97s model from 0 to 100 when using this standard. This allows the black colours as measured off the display faceplate to appropriately represent a visual black. Several experts have recommended this rescaling (Johnson 1996, Fairchild 1997) and it is common practice is the colour reproduction industry.

Note that is problematic to implement only veiling glare and not a viewing condition model and rescaling since this is NOT compliant with either CIE colour measurement or colour appearance recommendations. Instead it represents an intermediate physical measurement that does not represent colour appearance, but are dependent upon viewing conditions that colour appearance models describe.

Annex F
(informative)
Bibliography

"An Analytical Model for the Colorimetric Characterisation of Colour CRTs" by Ricardo Motta, Rochester Institute of Technology, 1991.

"A Standard Default Colour Space for the Internet: sRGB" Michael Stokes, Matthew Anderson, Srinivasan Chandrasekar, and Ricardo Motta, http://www.w3.org/Graphics/Color/sRGB.html

"Colour management in graphic arts and publishing" Tony Johnson, Pira International, Surrey England, 1996

"The Structure of the CIE 1997 Colour Appearance Model (CIECAM97)", R.W.G. Hunt and M.R. Luo, Proceedings of the CIE Expert Symposium '97, Scottsdale, 1997

"The digital to radiometric transfer function for computer controlled CRT displays," R. Berns and N Katoh, Proceedings of the CIE Expert Symposium '97, Scottsdale, 1997

"Progress Report of CIE TC1-34 with an Introduction of the CIECAM97s Colour Appearance Model," M. Fairchild, Proceedings of the CIE Expert Symposium '97, Scottsdale, 1997

"Reconsideration of CRT Monitor Characteristics," N. Katoh and T. Deguchi, Proceedings of Fifth Color Imaging Conference, IS&T/SID, Scottsdale, 1997

Color Management in Microsoft® Windows® Operating Systems

An Overview of Microsoft Image Color Management Technology

White Paper, April 1997

Download this document in Microsoft Word (.DOC) format (self-extracting, 225K).

Contents:

Introduction to Color Management

Color Is Pervasive Across Media, Yet Difficult to Reproduce Consistently

Over the years, magazines, newspapers, television, computers and, now, the Internet have all made the transition from black and white to color.

Now that all of these media use color, they all provide professional designers with the challenge of finding a way to get consistent color from page to screen to printer and beyond. Consistent color across various displays and types of output is critical to success. For example, in the publishing industry, consistent color throughout the commercial publishing process will save both time and money. Designers want to ensure that their clients' printed material will produce the same results when the job is passed to the service bureau, trade shop, and printer and that it will also look great when it's made available on the Internet.

The same is true for business professionals developing color presentations, or consumers wanting to buy products from an Internet site. All of these users expect "true" or what-you-see-is-what-you-get (WYSIWYG) computer color across all input and output peripherals and across various publishing and productivity applications. The computer industry has increased expectations for WYSIWYG graphics by achieving consistency in black-and-white publishing.

With color, however, WYSIWYG results across scanners, monitors, applications, and printers are often difficult, or impossible, to achieve for two reasons:

- **Different illuminants and colorants.** There is no color without light. White light contains the three components of color, namely red, green, and blue (RGB), and the perception of color is based on which of these wavelengths reach our eyes.

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Monitors and scanners are based on the "additive" color system using RGB, starting with black and then adding red, green, and blue to achieve color. Full saturation of RGB gives the perception of white, and images are created that radiate varying amounts of RGB.

Printers are based on the "subtractive" color system, usually using the colors cyan, magenta, yellow, and black (CMYK). Printed material creates images by reflecting light off of substances such as ink, dye, wax, and toner. Printers begin with white (the presence of white light) and subtract RGB to achieve colors and black. Cyan, for instance, subtracts red and allows the reflection of green and blue.

Both RGB and CMYK are known as device-dependent color systems or "color spaces."

Monitors can look different from one another for a variety of reasons, such as variances in the phosphors used to radiate the light and different bit depths. Printers can also give different results depending on a number of factors, such as the media used and the inks.

- **Different gamuts.** Each device, whether a scanner, monitor, or printer, has a particular range of colors that it is capable of producing, known as the device gamut. The gamut of a device is determined by the physical characteristics of the device itself, as well as the ambient lighting (for instance, the colors may appear rich in a dimly lit room and washed out in bright viewing conditions).

  A low-cost color monitor can, in many cases, reproduce nearly twice the number of colors as a multimillion dollar printing press, because the gamut of the monitor is superior to that of the press.

  The gamuts of devices of the same types may vary. For instance, the gamuts of scanners depend on the technology used (flatbed, drum, charge-coupled device) as well as the media scanned (reflective vs. transparent). With monitors, the gamut depends on the composition of the phosphors. With printers, the gamut varies depending on the inks and media used.

Because color science is so complex, it is impossible to completely eliminate these differences. However, there is a way to improve the situation - a color management system. A color management system (CMS) performs three main functions:

- Maps colors between devices that have different gamuts (e.g., scanners and monitors)
- Transforms colors from one color space to another (e.g., RGB to CMYK)
- Provides accurate on-screen or print previews that allow for corrective action

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Why Color Management is Required

Color Management at the Operating System-Level Brings Advantages Over

Application-Specific Color

In the publishing process, images and graphics are captured by scanners and digital cameras as well as from CDs, and they are brought together in editing and composition packages. From here, design professionals use a variety of proofing systems to simulate the final printed output and, ultimately, generate film for plate generation for final delivery to commercial printing presses. Designers also take these graphics to the Internet. Business and home users are likely to deliver their final graphics to a color printer, to the Internet, or to an intranet in corporate environments.

The publishing process is summarized in the following figure:

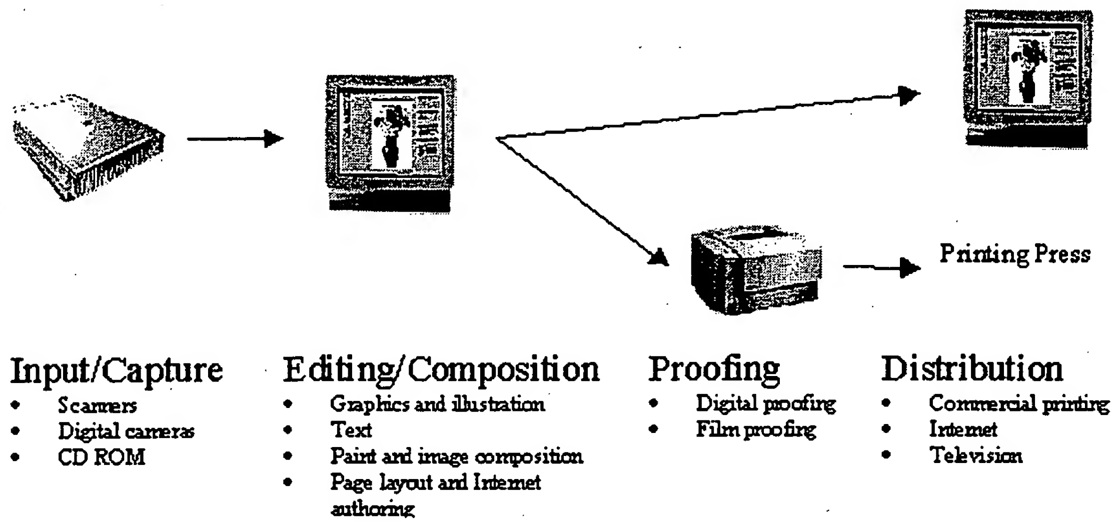
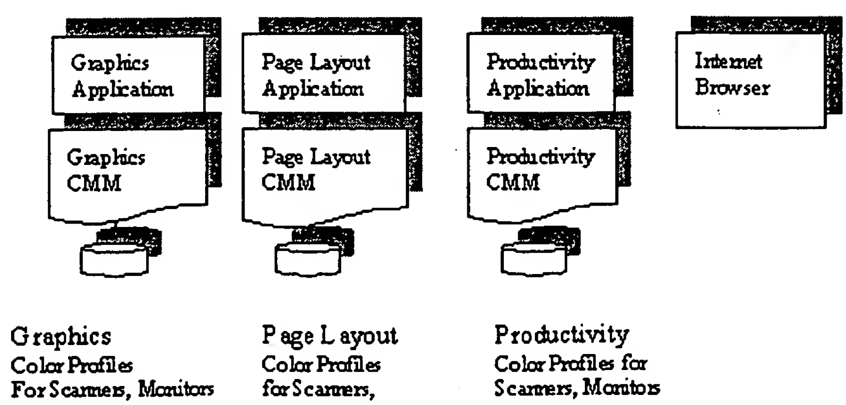


Figure 1. The publishing process

Being able to consistently reproduce color across scanners, monitors, printers, and applications sounds like a simple goal, but without a color management system in the operating system, it's difficult to achieve.

Without a standard CMS, each application writes to a different proprietary color management system with little or no interaction with the operating system. Each application generates its own color profiles, limiting the ability for consistent color interchange throughout the publishing process, which includes scanning, editing and composition, proofing, and distribution. The applications may produce different results.



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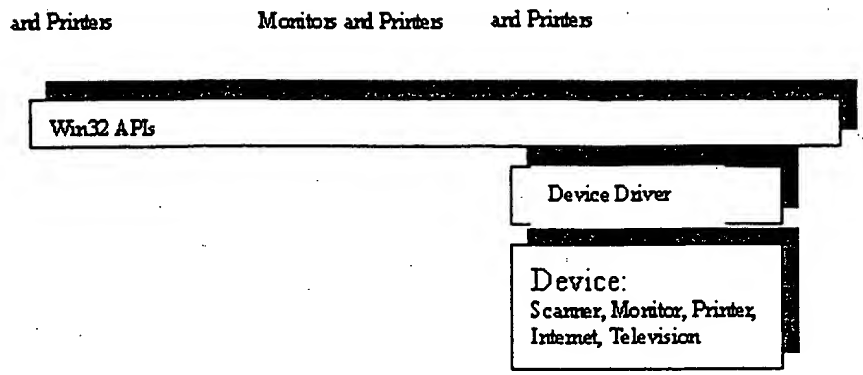

Figure 2. Application-specific color management

In addition, each application must supply profiles for all kinds of devices, as well as profile generation tools for all types of devices, a disadvantage to both the application developer and to the user.

As a result of each application generating its own profiles for every conceivable device, and in the absence of consistent interchange between devices, acceptable color on the output is achieved largely through trial and error.

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Image Color Management Features

Enhanced Color Support for Publishing and Productivity Applications

ICM 1.0
Microsoft Corporation's current implementation of color management support was released in the Microsoft® Windows® 95 operating system as Image Color Matching (ICM) 1.0, an API to which third-party applications can write. This version of ICM was designed to address the needs of applications that work with RGB, to work seamlessly for the end user, and to enable simple support from application developers.

ICM 1.0 supports profiles that conform to the International Color Consortium (ICC) profile specification. The ICC profile specification is a cross-platform industry standard that accurately and consistently characterizes devices including scanners, monitors, and printers. The ICC started in 1993 as an organization to promote color standards with desktop applications.

ICM profiles must be installed for all of the color devices on the user's system, and applications that need to portray colors accurately must support the ICM 1.0 API.

The ICM 1.0 technology supports alternate color management modules (CMMs) that transform color information between different color spaces, such as the RGB colors captured by the scanner to the slightly different RGB values displayed on a monitor or sent to printers.

ICM 2.0
After listening to customers and application vendors, Microsoft enhanced the capability of ICM to provide increased functionality and performance and decided

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to bring it to the Windows NT® 5.0 and Windows 98 operating systems, extending the reach beyond Windows 95. Microsoft also wanted support for more color spaces (beyond RGB to CMYK, to device-independent color spaces such as CIELAB, a theoretical color space defined by the Commission Internationale de L'Eclairage, or CIE), as well as support for additional colors for processes such as HiFi Color.

Higher-Quality Color Management Module

ICM 2.0 supports the LinoColor color management module (CMM) as the default CMM. The CMM transforms color information across various devices. Linotype-Hell AG is one of the leading vendors of color technology in the publishing and prepress world. This technology is now expected to become available to all applications that support the ICM 2.0 API.

Applications will now have the ability to support all color spaces — RGB and CMYK, as well as device-independent color spaces such as those defined by the CIE, such as CIELAB.

ICM 2.0 will support up to eight input and output color channels for enhanced printing processes such as HiFi Color.

Support for Industry Standards Ensures Cross-Platform Compatibility

By licensing the industry-standard LinoColorCMM and continuing support for International Color Consortium (ICC) profiles, Microsoft is helping to ensure that applications that support ICM 2.0 will be compatible with other platforms, a fact that is important because multiple platforms may be used throughout the color publishing process.

Like ICM 1.0, ICM 2.0 supports the ICC profiles, allowing the same device profiles to be used across platforms and ensuring better color management throughout the publishing process. Microsoft plans to recommend that all hardware vendors ship these profiles with their Windows-compatible peripherals, ensuring a high level of compatibility and availability.

***Ease of Use for Productivity Application End Users, Publishing Professionals,
and Developers***

For productivity and entry-level publishing applications, ICM 2.0 can be configured to be completely transparent to the end user.

For professional publishing applications, full manual control is available, in each case ensuring color consistency across devices and platforms. In addition, for professional publishers, ICM provides an easy-to-use selection method for choosing alternative profiles.

For application developers, the ICM API is simple to implement.

Modular, Extensible Architecture

Applications will have the ability to support two levels of API - one that deals only in RGB, and one that works in multiple color spaces. As developers take advantage of these enhanced capabilities, users will be able to manage device profiles and

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select an alternate CMM for their color transformations.

The architecture is summarized in the following figure:

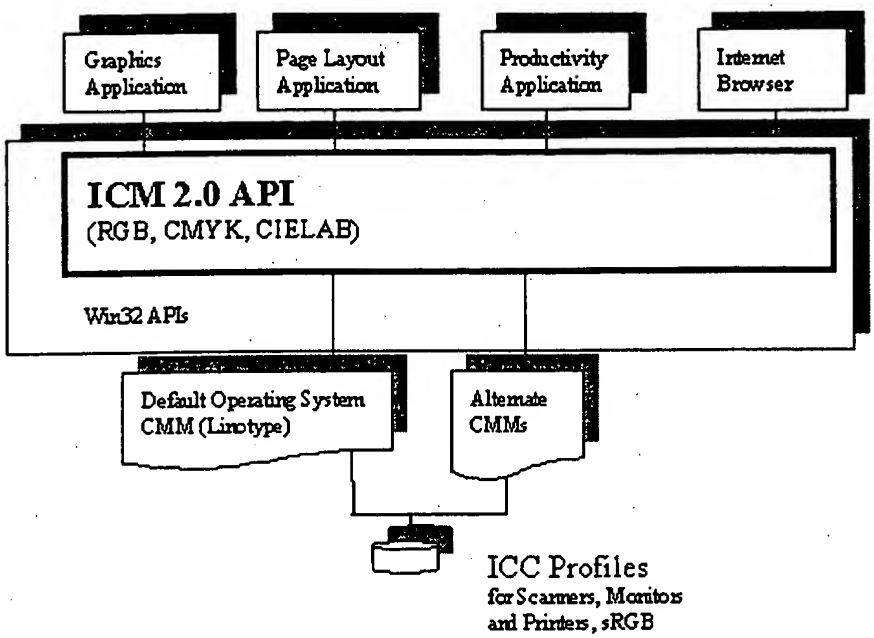

Figure 3. ICM 2.0 technology overview

Support for a Complementary Standard Color Space: sRGB

ICM provides a standard way to manage color between any input device (e.g., scanner) and output device (e.g., monitor), including the ability to embed ICC profiles directly into the image or to pass the ICC profile directly to the application. The application, along with ICM and the rendering intent, generates a profile that ensures accurate color representation between the input and output device.

Embedding the ICC profile into each image is an excellent way to ensure that the color profile information is being passed along throughout the publishing process. However, the additional overhead it adds to the image may be unacceptable for transmission over the Internet. Also, several image formats currently do not support embedded ICC profiles, which makes it very difficult to represent the color image accurately.

Hewlett-Packard Co. and Microsoft have created a new color space, sRGB, that is meant to complement current color management strategies by enabling another method of handling color in the operating system and the Internet. It will provide good quality and backward compatibility, with minimum transmission and system overhead. Based on a calibrated colorimetric RGB color space, which is well-suited to monitors, television, scanners, digital cameras and printing systems, such a space can be supported with minimum cost to software and hardware vendors.

In addition, both companies have worked with the World Wide Web Consortium (W3C) to ensure that sRGB is available to all vendors. sRGB is now the standard color space for HTML 3.2 and Cascading Style Sheets (CSS) 1.0, and it is freely available to any software or hardware vendor.

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Microsoft also plans to make sRGB the default color space in future versions of its Windows 95 and Windows NT operating systems for all color images that do not have an embedded ICC profile, or for images that are not specifically tagged with other color information. This will help ensure that colors are represented in a way that looks best on the widest range of devices.

A summary of when sRGB is expected to be used is outlined in Figure 4. The "source" referred to in the figure could be a scanner, and the "destination" could be a monitor.

	Image has source color profile	**Image has no source color profile**
Destination has color profile	Use both profiles in the color mapping	Use sRGB as the source profile and use the destination profile in the color mapping
Destination has no color profile	Use the source profile and use sRGB as the destination profile in the color mapping	Do nothing (assume sRGB is the profile for source and destination)

Figure 4. Understanding when sRGB is the default color space in the color mapping process

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For More Information

- *Microsoft ICM 2.0 SDK Web site:*
  - *http://www.microsoft.com/msdn/sdk/icm20.htm*
- *International Color Consortium (ICC) Web site:*
  - *http://www.color.org/*
- *World Wide Web Consortium (W3C) HTML 3.2 Web site:*
  - *http://www.w3.org/pub/WWW/TR/REC-html32.html*
- *W3C CSS 1.0 Web site:*
  - *http://www.w3.org/pub/WWW/TR/REC-CSS1*
- *W3C sRGB Web site:*
  - *http://www.w3.org/Graphics/Color/sRGB.html*

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Glossary

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Color spaces. *A theoretical three-dimensional color system, whereby the axes of color, hue, saturation, and brightness can be represented.*

Colorant. *A dye or pigment that causes a color to appear.*

Color management module (CMM). *A component in a color management system (CMS) that transforms color data from one color space to another.*

Cascading Style Sheets (CSS). *CSS1 is a simple style sheet mechanism that allows authors and readers to attach style (e.g., fonts, colors, and spacing) to HTML documents. The CSS1 language is human-readable and writable, and expresses style in common desktop publishing terminology.*

CIE. *Commission Internationale de L'Eclairage, an organization for setting standards for color measurement.*

CIELAB. *A theoretical color space defined by the CIE.*

Colorimetric. *A color space whereby one can measure the color values. Colorimeters are devices used to measure the color values on a monitor or on printed material.*

CMYK. *Cyan, magenta, yellow, and black are the four-color process inks used in color printing. Cyan absorbs the red hues, magenta absorbs the green hues, yellow absorbs the blue hues. Black is an ink whose colorant has no apparent hue.*

HiFi Color. *HiFi Color is a variety of print processes that achieve superior visual appearance of color and imagery not possible with conventional four-color process printing. HiFi Color offers an expanded color gamut compared with traditional printing processes.*

HTML 3.2. *Hypertext markup language is the open-standards language for describing the hyperlinking on the Internet. The standards body that evolves the language is known as the World Wide Web Consortium (W3C). Version 3.2 is the current version of the language in the industry.*

International Color Consortium (ICC). *The International Color Consortium was established in 1993 by eight industry vendors for the purpose of creating, promoting and encouraging the standardization and evolution of an open, vendor-neutral, cross-platform color management system architecture and components.*

RGB. *Red, green, and blue is the color system used in scanners, digital cameras, and printers.*

World Wide Web Consortium (W3C). *The standards body responsible for advancing the Internet standards.*

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Color Management

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Colorspace Interchange Using sRGB

By

Gary Starkweather

Color management technology for personal computers is now becoming available on a broad basis. Much has been written about how to get the best color, what transforms to use etc. Among the most recent additions to editorial content has been issues regarding the use of sRGB as a standard interchange colorspace. Several articles have been rather shrill in denouncing or detracting from sRGB's inherent value. This is unfortunate and this article is intended to explain both the benefits and concerns of using any colorspace for color data interchange in addition to using sRGB as that space. It is hoped that the material contained here will help the reader understand why sRGB has value as well as what its limitations are. No "standard," whatever it is comes without some limitations. The appropriate solution is that which offers the most benefit and the least trouble. It is felt that sRGB offers an acceptable solution at this time. The purpose of this brief paper is not a deep technical discussion which is available in detail along with other references at www.srgb.com but an explanation of the choices available and why the sRGB choice was made.

Color interchange spaces have the benefit that all color devices can conveniently exchange color data in a common format. This foregoes the need to constantly translate between color spaces due to difference data representations in the various devices. The CIE system (Commission Internationale de l'Eclairage or International Commission on Illumination) provides a solid scientific foundation for color data based on careful experimental measurements of human observers. However, there are a number of ways to utilize the CIE data. The CIELAB and CIELUV systems are but two systems intended to provide color data that at least approximates perceptual uniformity. However, two color patches having highly similar LAB values do not necessarily appear the same depending on visual conditions. The color of the illuminant (white point), the absolute level of the scene irradiance (visually the illuminance), the surrounding colors etc. all serve to defeat the "perfect match" unless the initial and test conditions are identical. Photographs are often quite acceptable to most users but rarely does one travel back out to the original scene of the photograph and check to see that the leaf e.g., and the photograph of the leaf are identical. The appearance of the leaf in the photo is what is critical in most cases. This will not necessarily be true for demanding commercial applications such as buying clothing, for example. One can usually benefit from the old axiom in graphic arts originally coined by Professor Miles Southworth of RIT. The axiom states "that "clean and bright is always right" and "dull and gray is not the way."

So why not just pick CIELAB, for example, to become the interchange space. First of all, this in and of itself would not suffice. One would need to specify a white point and illuminance level of the scene in order to have any reasonable chance of achieving a proper representation. The other problem with CIELAB is that getting data into and from it requires the use of cube roots or raising values to the third power. It would be nice to be

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able to store color data in a form that when one wanted to view it, it was indeed ready for viewing under most reasonable conditions. Storing data in CIELAB would require converting every pixel through a set of power function routines. This might not only be time consuming but could be fraught with possible errors depending on who was doing the conversion. Another approach that might satisfy those concerned with gamut issues (CIE carries the full gamut extent of the visual system), would be to let the data conform to a theoretical display such as a laser display. Laser's have virtually monochromatic output and therefore the primaries of a laser display would reside on the spectrum locus of the CIE diagram as shown in figure 1.

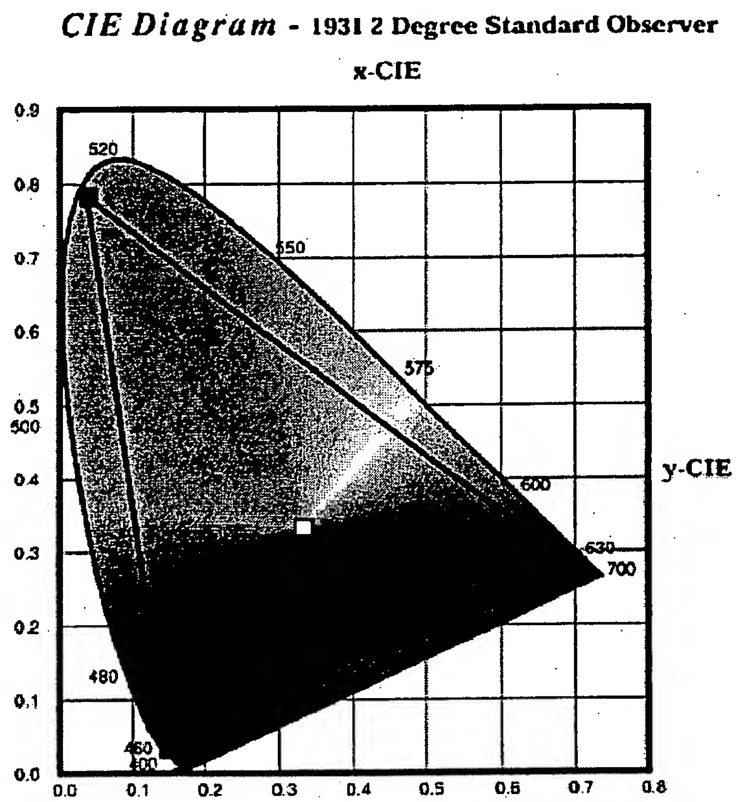

Figure 1 – Laser Display Color Gamut

Using the 633 nm. output of Helium-Neon, the 514 nm. output of Argon and the 442 nm. output of Helium-Cadmium would make for an impressive color gamut. Other laser lines such as those of Krypton etc. could also be considered but would not alter the conclusions of the argument.

First, in utilizing a laser display the data can be carried across devices without gamut loss. That is the data would stay around as positive numbers. No commercial displays, scanners or printers exceed or come close to exceeding the laser display gamut. The problem comes from the fact that no device normal users will get their hands on has this

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gamut. Thus data in the laser display colorspace will have to be converted for display and print. This requires additional calculation again, however, not as complex as with CIELAB. Gamut mapping would be required however for destination devices. Thus, we have the calculation and representation issues of CIELAB and the large gamut but non-device representative nature of the laser display. What other choices are available? Today, most of the devices on which images are viewed are displays. The predominant display technology today (~80%) are the cathode ray tube or CRT display. Color flat panels whether passive or active matrix type also try to come close to the color CRT model. High definition television or HDTV will use a set of phosphors known as ITU-R 709.BT. The color gamut of these phosphors is shown on a 1931 CIE diagram in figure 2.

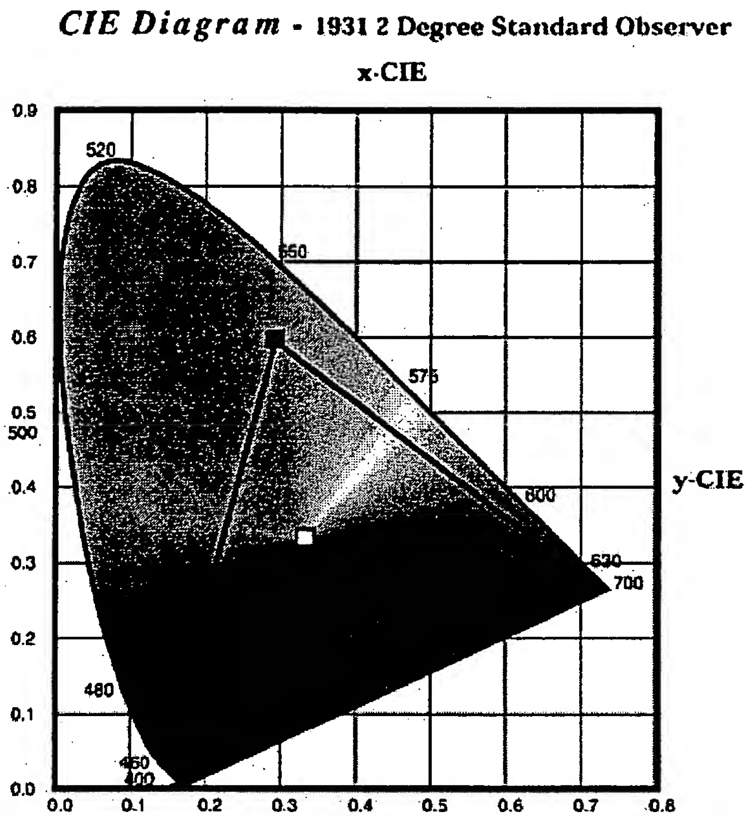

Figure 2 – sRGB Color Gamut

From the spectral and colorimetric characteristics of these phosphors, a standard known as sRGB was proposed and adopted by a number of companies such as Hewlett-Packard and Microsoft. The reader can visit the web site at www.srgb.com for additional information.

First, sRGB is not believed to be a perfect interchange space but it does possess a number of salient features that should be appreciated. First, as can be seen in figure 3, it does not differ much from the old Apple 13" RGB monitor gamut.

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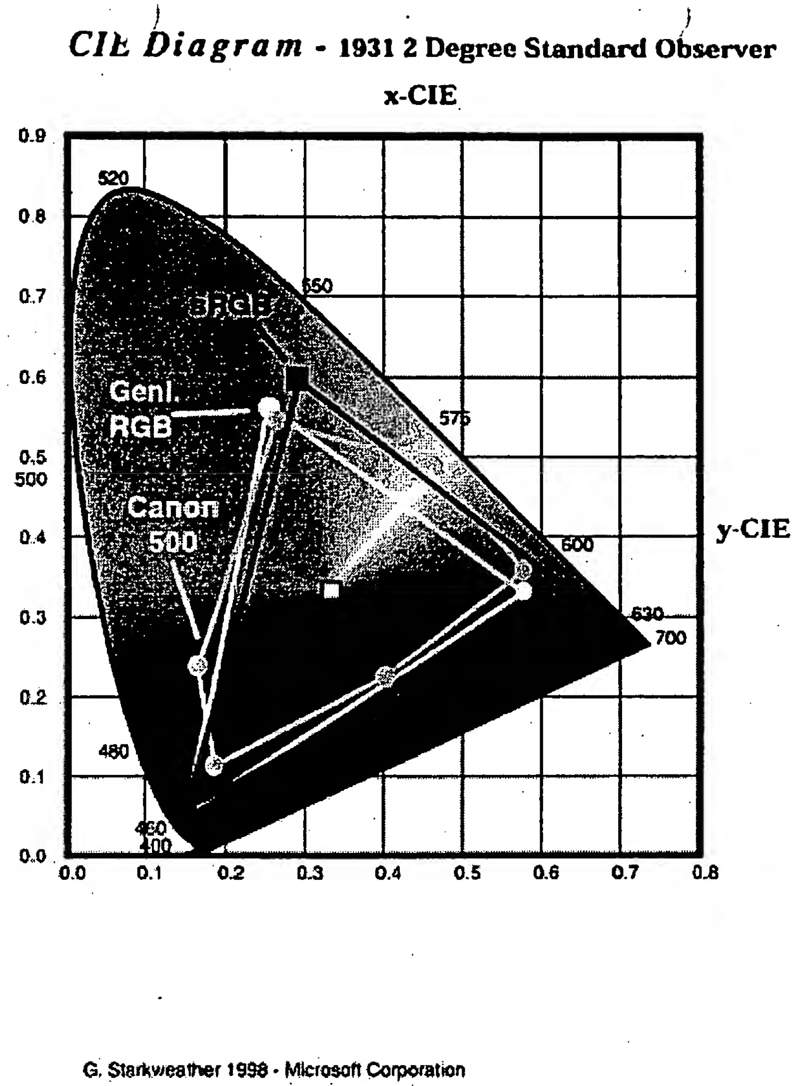

Figure 3 – Color Gamut Comparisons

Thus, those people imagining that this gamut is strikingly different from their CRT do not need to worry. Furthermore, the sRGB standard has built into it the illuminance levels and other visual environment features that are the most common among the consumer and general user community. Perhaps the most controversial parts of sRGB have to do with gamut limitations and the gamma value built into the standard. Let's take the gamma value first. The sRGB gamma value of 2.2 provides pictures that look darker on a monitor set to a lower gamma value, say 1.8 or even 1.4. This is an easy change of course but the gamma of 2.2 was chosen for good viewing conditions and an attempt at perceptual uniformity. Equal perceptual steps in a grayscale image would tend to follow a gamma of 2.2 although not perfectly. To utilize the 2.2 gamma of sRGB some users will have to modify how they have worked in the past and this always presents some difficulties. The gamut issues are also of concern to many. They claim that the sRGB gamut is too limited and hence "clips" their output device's ability to reach its full potential. This is only true if one permits this to be the case. For example, in figure 3, a

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gamut of the venerable Canon CLC500 color copier/printer is shown along with sRGB and the old RGB realized on the first PC color monitors. Note that while some of the cyan colors are limited by sRGB, the brightest greens and reds are output device limited not sRGB limited.

In reality, there are devices such as film scanners with their high quality images that exceed the sRGB gamut. This is not a reason to toss out the sRGB standard. When colors go out of gamut mathematically, they can either exceed an accepted maximum usable value like 255 or fall below an accepted minimum value such as zero. Going out of gamut does not cause the data to disappear from the universe unless the data is purposely "clipped" to an artificial lower and upper bound. If one keeps the data that goes out of gamut then when devices that exceed the sRGB must be dealt with, the data is available for use in the necessary calculations. Therefore, a major concern about any gamut that can be exceeded is avoided. One of the important benefits of sRGB is often overlooked or not mentioned by its detractors. That benefit is that most people using personal computers spend a great deal of time either viewing, editing or otherwise dealing with color data on their screens. Since the sRGB colorspace is or can be quite representative of a majority of displays, data in sRGB can be directly viewed on their monitors without modification. This is an important advantage in that purveyors of color data can place their content in sRGB and know that in most instances when it is viewed on computer monitors it is in a "ready-to-go" state. No cube roots, table look-ups or other processing is required. Until color data processing is so pervasive and fast as to be both spatially and temporally transparent to the user this is and will be a substantial benefit. If the phone system were like much of today's proposed color spaces, we would print and display phone numbers in a form that would require multiplication and division combined with addition and subtraction to get the number we needed to dial. Why not just give the user the 767-2345 number instead of a code they must be prepared to process? SRGB is aimed at providing an acceptable not all encompassing solution to users and information suppliers alike.

In summary, sRGB is not a perfect color space. However, it is representative of the majority of devices on which color is and will be viewed. Furthermore, sRGB is a profile that is compliant with ICC profiles and current color management systems. Carrying around out of gamut data would permit one to utilize the full color capability of their devices, albeit at some risk. The risk is that my red may be brighter than your red since we have different printers. Utilizing in-gamut sRGB data means that we can ensure a substantial degree of consistency as well as have our output expectations reasonably well set at the point of creation (the display). More sophisticated color management tools not usually in the interest domain of ordinary users would permit utilizing data outside the sRGB gamut for those brightest of colors for which the user may have paid a lot to realize. Thus, properly used, sRGB provides a consistency, speed and quality level that should satisfy the majority of consumers who want quality images with minimum hassle. For those for whom color is a highly polished skill from which they either earn a living or enjoy in its own right, sRGB does not foreclose their ability to add value to the imaging chain. Using sRGB is aimed at achieving the equivalent experience of dropping off photos for printing. You are not asked what temperature you desire for the first developer or how many stops you wish to "push" the development process. Aristotle did not likely

comprehend the era of digital color but his statement that "simplicity is the truest elegance" could apply to color imaging as well. I think he would appreciate sRGB.

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THE SYSTEMS PROGRAMMING SERIES

Computer Graphics: Principles and Practice

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13 Achromatic and Colored Light

The growth of raster graphics has made color and gray scale an integral part of contemporary computer graphics. Color is an immensely complex subject, one that draws on concepts and results from physics, physiology, psychology, art, and graphic design. Many researchers' careers have been fruitfully devoted to developing theories, measurement techniques, and standards for color. In this chapter, we introduce some of the areas of color that are most relevant to computer graphics.

The color of an object depends not only on the object itself, but also on the light source illuminating it, on the color of the surrounding area, and on the human visual system. Furthermore, some objects reflect light (wall, desk, paper), whereas others also transmit light (cellophane, glass). When a surface that reflects only pure blue light is illuminated with pure red light, it appears black. Similarly, a pure green light viewed through glass that transmits only pure red will also appear black. We postpone some of these issues by starting our discussion with achromatic sensations—that is, those described as black, gray, and white.

13.1 ACHROMATIC LIGHT

Achromatic light is what we see on a black-and-white television set or display monitor. An observer of achromatic light normally experiences none of the sensations we associate with red, blue, yellow, and so on. Quantity of light is the only attribute of achromatic light. Quantity of light can be discussed in the physics sense of energy, in which case the terms *intensity* and *luminance* are used, or in the psychological sense of perceived intensity, in which case the term *brightness* is used. As we shall discuss shortly, these two concepts are

related but are not the same. It is useful to associate a scalar with different intensity levels, defining 0 as black and 1 as white; intensity levels between 0 and 1 represent different grays.

A black-and-white television can produce many different intensities at a single pixel position. Line printers, pen plotters, and electrostatic plotters produce only two levels: the white (or light gray) of the paper and the black (or dark gray) of the ink or toner deposited on the paper. Certain techniques, discussed in later sections, allow such inherently *bilevel* devices to produce additional intensity levels.

13.1.1 Selecting Intensities—Gamma Correction

Suppose we want to display 256 different intensities. Which 256 intensity levels should we use? We surely do not want 128 in the range of 0 to 0.1 and 128 more in the range of 0.9 to 1.0, since the transition from 0.1 to 0.9 would certainly appear discontinuous. We might initially distribute the levels evenly over the range 0 to 1, but this choice ignores an important characteristic of the eye: that it is sensitive to ratios of intensity levels rather than to absolute values of intensity. That is, we perceive the intensities 0.10 and 0.11 as differing just as much as the intensities 0.50 and 0.55. (This nonlinearity is easy to observe: Cycle through the settings on a three-way 50–100–150-watt lightbulb; you will see that the step from 50 to 100 seems much greater than the step from 100 to 150.) On a brightness (that is, perceived intensity) scale, the differences between intensities of 0.10 and 0.11 and between intensities of 0.50 and 0.55 are equal. Therefore, the intensity levels should be spaced logarithmically rather than linearly, to achieve equal steps in brightness.

To find 256 intensities starting with the lowest attainable intensity I_0 and going to a maximum intensity of 1.0, with each intensity r times higher than the preceding intensity, we use the following relations:

$$I_0 = I_0,\ I_1 = rI_0,\ I_2 = rI_1 = r^2I_0,\ I_3 = rI_2 = r^3I_0,\ \ldots,\ I_{255} = r^{255}I_0 = 1. \quad (13.1)$$

Therefore,

$$r = (1/I_0)^{1/255},\ I_j = r^jI_0 = (1/I_0)^{j/255}\ I_0 = I_0^{(255-j)/255} \quad \text{for } 0 \le j \le 255, \quad (13.2)$$

and in general for $n + 1$ intensities,

$$r = (1/I_0)^{1/n},\ I_j = I_0^{(n-j)/n} \quad \text{for } 0 \le j \le n. \quad (13.3)$$

With just four intensities ($n = 3$) and an I_0 of $\frac{1}{8}$ (an unrealistically large value chosen for illustration only), Eq. (13.3) tells us that $r = 2$, yielding intensity values of $\frac{1}{8}, \frac{1}{4}, \frac{1}{2}$, and 1.

The minimum attainable intensity I_0 for a CRT is anywhere from about $\frac{1}{200}$ up to $\frac{1}{40}$ of the maximum intensity of 1.0. Therefore, typical values of I_0 are between 0.005 and 0.025. The minimum is not 0, because of light reflection from the phosphor within the CRT. The ratio between the maximum and minimum intensities is called the *dynamic range*. The exact value for a specific CRT can be found by displaying a square of white on a field of black and measuring the two intensities with a photometer. This measurement is taken in a completely darkened room, so that reflected ambient light does not affect the intensities. With an I_0 of 0.02, corresponding to a dynamic range of 50, Eq. (13.2) yields $r = 1.0154595\ldots$, and the first few and last two intensities of the 256 intensities from Eq. (13.1) are 0.0200, 0.0203, 0.0206, 0.0209, 0.0213, 0.0216, ..., 0.9848, 1.0000.

Displaying the intensities defined by Eq. (13.1) on a CRT is a tricky process, and recording them on film is even more difficult, because of the nonlinearities in the CRT and film. For instance, the intensity of light output by a phosphor is related to the number of electrons N in the beam by

$$\boxed{I = kN^{\gamma}} \tag{13.4}$$

for constants k and γ. The value of γ is in the range 2.2 to 2.5 for most CRTs. The number of electrons N is proportional to the control-grid voltage, which is in turn proportional to the value V specified for the pixel. Therefore, for some other constant K,

$$I = KV^{\gamma}, \text{ or } V = (I/K)^{1/\gamma}. \tag{13.5}$$

Now, given a desired intensity I, we first determine the nearest I_j by searching through a table of the available intensities as calculated from Eq. (13.1) or from its equivalent:

$$j = ROUND(log_r(I/I_0)). \tag{13.6}$$

After j is found, we calculate

$$I_j = r^j I_0. \tag{13.7}$$

The next step is to determine the pixel value V_j needed to create the intensity I_j, by using Eq. (13.5):

$$V_j = ROUND\,((I_j/K)^{1/\gamma}). \tag{13.8}$$

If the raster display has no look-up table, then V_j is placed in the appropriate pixels. If there is a look-up table, then j is placed in the pixel and V_j is placed in entry j of the table.

The values of K, γ, and I_0 depend on the CRT in use, so in practice the look-up table is loaded by a method based on actual measurement of intensities [CATM79; COWA83; HALL89]. Use of the look-up table in this general manner is called *gamma correction*, so named for the exponent in Eq. (13.4). If the display has hardware gamma correction, then I_j rather than V_j is placed in either the refresh buffer or look-up table.

Without the use of ratio-based intensity values and gamma correction, quantization errors (from approximating a true intensity value with a displayable intensity value) will be more conspicuous near black than near white. For instance, with 4 bits and hence 16 intensities, a quantization round-off error of as much as $\frac{1}{32} = 0.031$ is possible. This is 50 percent of intensity value $\frac{1}{16}$, and only 3 percent of intensity value 1.0. Using the ratio-based intensities and gamma correction, the maximum quantization error as a percentage of brightness (perceived intensity) is constant.

A natural question is, "How many intensities are enough?" By "enough," we mean the number needed to reproduce a continuous-tone black-and-white image such that the reproduction appears to be continuous. This appearance is achieved when the ratio r is 1.01 or less (below this ratio, the eye cannot distinguish between intensities I_j and I_{j+1}) [WYSZ82, p. 569]. Thus, the appropriate value for n, the number of intensity levels, is found by equating r to 1.01 in Eq. (13.3):

$$r = (1/I_0)^{1/n} \quad \text{or} \quad 1.01 = (1/I_0)^{1/n}. \tag{13.9}$$

TABLE 13.1 DYNAMIC RANGE ($1/I_0$) AND NUMBER OF REQUIRED INTENSITIES $n = \log_{1.01}(1/I_0)$ FOR SEVERAL DISPLAY MEDIA

Display media	Typical dynamic range	Number of intensities, n
CRT	50–200	400–530
Photographic prints	100	465
Photographic slides	1000	700
Coated paper printed in B/W*	100	465
Coated paper printed in color	50	400
Newsprint printed in B/W	10	234

*B/W = black and white.

Solving for n gives

$$\boxed{n = \log_{1.01}(1/I_0),} \tag{13.10}$$

where $1/I_0$ is the dynamic range of the device.

The dynamic range $1/I_0$ for several display media, and the corresponding n, which is the number of intensity levels needed to maintain $r = 1.01$ and at the same time to use the full dynamic range, are shown in Table 13.1. These are theoretical values, assuming perfect reproduction processes. In practice, slight blurring due to ink bleeding and small amounts of random noise in the reproduction decreases n considerably for print media. For instance, Fig. 13.1 shows a continuous-tone photograph; and the succeeding five Figs. 13.2 to 13.6 reproduce the same photograph at 4, 8, 16, 32, and 64 intensity levels. With four and eight levels, the transitions or contours between one intensity level and the next are quite conspicuous, because the ratio r between successive intensities is considerably greater that the ideal 1.01. Contouring is barely detectable with 32 levels, and for these particular

Fig. 13.1 A continuous-tone photograph.

Fig. 13.2 A continuous-tone photograph reproduced with four intensity levels. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

Fig. 13.3 A continuous-tone photograph reproduced with eight intensity levels. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

Fig. 13.4 A continuous-tone photograph reproduced with 16 intensity levels. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

Fig. 13.5 A continuous-tone photograph reproduced with 32 intensity levels. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

Fig. 13.6 A continuous-tone photograph reproduced with 64 intensity levels. Differences from the picture in Fig. 13.5 are quite subtle. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

images disappears with 64. This suggests that 64 intensity levels is the absolute minimum needed for contour-free printing of continuous-tone black-and-white images on paper such as is used in this book. For a well-adjusted CRT in a perfectly black room, however, the higher dynamic range means that many more levels are demanded.

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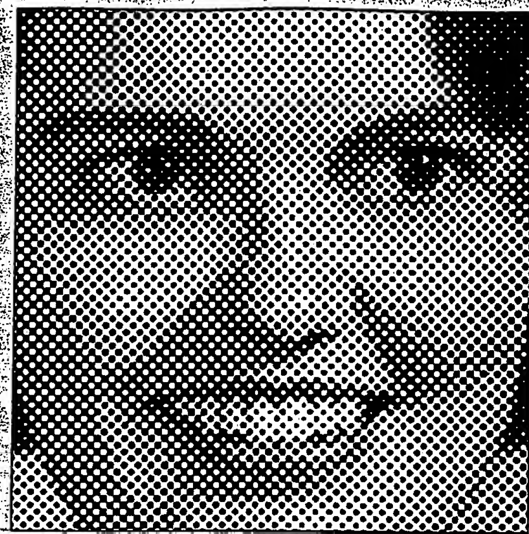

Fig. 13.7 Enlarged halftone pattern. Dot sizes vary inversely with intensity of original photograph. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

13.1.2 Halftone Approximation

Many displays and hardcopy devices are bilevel—they produce just two intensity levels—and even 2- or 3-bit-per-pixel raster displays produce fewer intensity levels than we might desire. How can we expand the range of available intensities? The answer lies in the *spatial integration* that our eyes perform. If we view a very small area from a sufficiently large viewing distance, our eyes average fine detail within the small area and record only the overall intensity of the area.

This phenomenon is exploited in printing black-and-white photographs in newspapers, magazines, and books, in a technique called *halftoning* (also called *clustered-dot ordered dither*[1] in computer graphics). Each small resolution unit is imprinted with a circle of black ink whose area is proportional to the blackness $1 - I$ (where I = intensity) of the area in the original photograph. Figure 13.7 shows part of a halftone pattern, greatly enlarged. Note that the pattern makes a 45° angle with the horizontal, called the *screen angle*. Newspaper halftones use 60 to 80 variable-sized and variable-shaped areas [ULIC87] per inch, whereas halftones in magazines and books use 110 to 200 per inch.

Graphics output devices can approximate the variable-area circles of halftone reproduction. For example, a 2×2 pixel area of a bilevel display can be used to produce five different intensity levels at the cost of halving the spatial resolution along each axis. The patterns shown in Fig. 13.8 can be used to fill the 2×2 areas with the number of "on" pixels that is proportional to the desired intensity. Figure 13.9 shows a face digitized as a 351×351 image array and displayed with 2×2 patterns.

An $n \times n$ group of bilevel pixels can provide $n^2 + 1$ intensity levels. In general, there is a tradeoff between spatial resolution and intensity resolution. The use of a 3×3 pattern

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[1]The "ordered dither" contrasts with "random dither," an infrequently used technique.

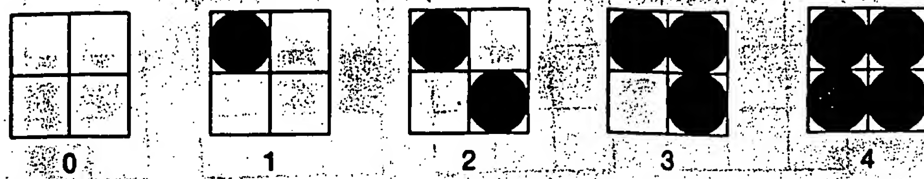

Fig. 13.8 Five intensity levels approximated with four 2 × 2 dither patterns.

cuts spatial resolution by one-third on each axis, but provides 10 intensity levels. Of course, the tradeoff choices are limited by our visual acuity (about 1 minute of arc in normal lighting), the distance from which the image is viewed, and the dots-per-inch resolution of the graphics device.

One possible set of patterns for the 3 × 3 case is shown in Fig. 13.10. Note that these patterns can be represented by the *dither matrix*

$$\begin{bmatrix} 6 & 8 & 4 \\ 1 & 0 & 3 \\ 5 & 2 & 7 \end{bmatrix} \tag{13.11}$$

To display an intensity I, we turn on all pixels whose values are less than I.

The $n \times n$ pixel patterns used to approximate the halftones must be designed not to introduce visual artifacts in an area of identical intensity values. For instance, if the pattern in Fig. 13.11 were used, rather than the one in Fig. 13.10, horizontal lines would appear in any large area of the image of intensity 3. Second, the patterns must form a *growth sequence* so that any pixel intensified for intensity level j is also intensified for all levels $k > j$. This minimizes the differences in the patterns for successive intensity levels, thereby minimizing the contouring effects. Third, the patterns must grow outward from the center, to create the effect of increasing dot size. Fourth, for hardcopy devices such as laser printers and film recorders that are poor at reproducing isolated "on" pixels, all pixels that are "on" for a

Fig. 13.9 A continuous-tone photograph, digitized to a resolution of 351 × 351 and displayed using the 2 × 2 patterns of Fig. 13.8. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

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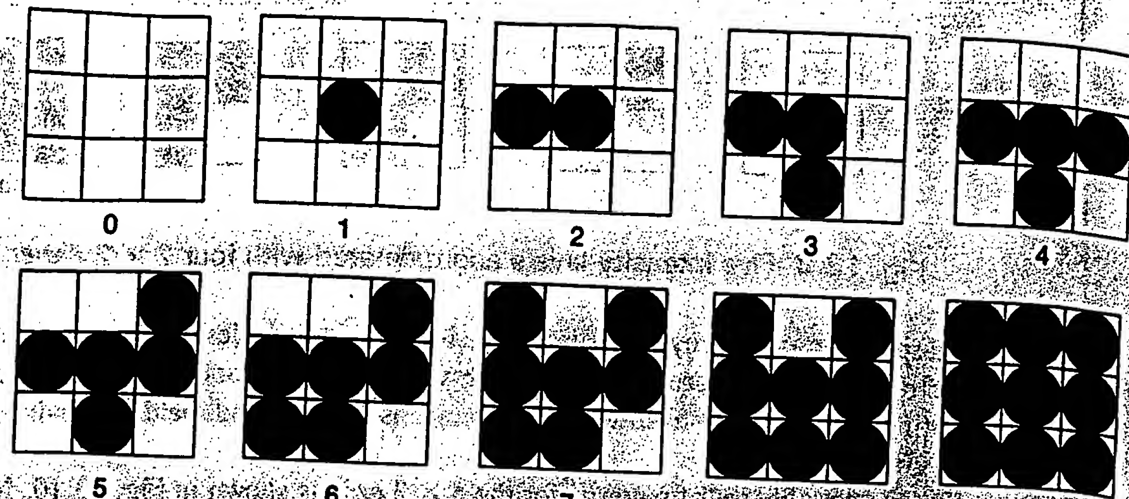

Fig. 13.10 Ten intensity levels approximated with 3 × 3 dither patterns.

particular intensity must be adjacent to other "on" pixels; a pattern such as that in Fig. 13.12 is not acceptable. This is the meaning of the term *clustered-dot* in "clustered-dot ordered dither." Holladay [HOLL80] has developed a widely used method for defining dither matrices for clustered-dot ordered dither. For high-quality reproduction of images, n must be 8 to 10, theoretically allowing 65 to 101 intensity levels. To achieve an effect equivalent to the 150-circle-per-inch printing screen, we thus require a resolution of from $150 \times 8 = 1200$ up to $150 \times 10 = 1500$ pixels per inch. High-quality film recorders can attain this resolution, but cannot actually show all the intensity levels because patterns made up of single black or white pixels may disappear.

Halftone approximation is not limited to bilevel displays. Consider a display with 2 bits per pixel and hence four intensity levels. The halftone technique can be used to increase the number of intensity levels. If we use a 2×2 pattern, we have a total of 4 pixels at our disposal, each of which can take on three values besides black; this allows us to display $4 \times 3 + 1 = 13$ intensities. One possible set of growth sequence patterns in this situation is shown in Fig. 13.13.

Unlike a laser printer, a CRT display is quite able to display individual dots. Hence, the clustering requirement on the patterns discussed previously can be relaxed and *dispersed-dot ordered dither* can be used. There are many possible dither matrices: Bayer [BAYE73] has developed dither matrices that minimize the texture introduced into the displayed images. For the 2×2 case, the dither matrix, called $D^{(2)}$, is

$$D^{(2)} = \begin{bmatrix} 0 & 2 \\ 3 & 1 \end{bmatrix}. \tag{13.12}$$

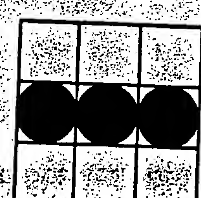

Fig. 13.11 A 3 × 3 dither pattern inappropriate for halftoning.

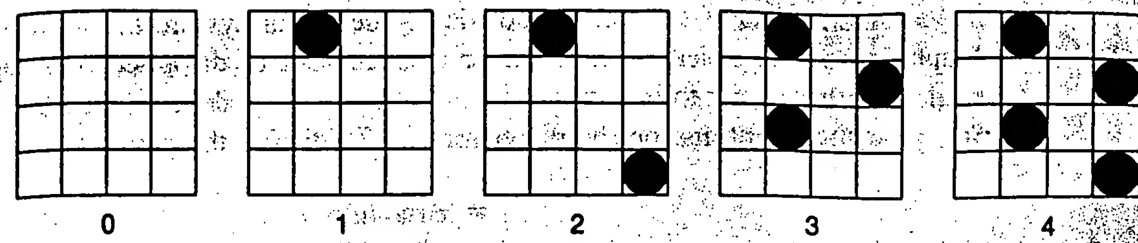

Fig. 13.12 Part of a 4 × 4 ordered dither dot pattern in which several of the patterns have single, nonadjacent dots. Such disconnected patterns are unacceptable for halftoning on laser printers and for printing presses.

This represents the set of patterns of Figure 13.8.

Larger dither matrices can be found using a recurrence relation [JUDI74] to compute $D^{(2n)}$ from $D^{(n)}$. With $U^{(n)}$ defined as an $n \times n$ matrix of 1s, that is,

$$U^{(n)} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ \vdots & & & & \vdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix}, \tag{13.13}$$

the recurrence relation is

$$D^{(n)} = \begin{bmatrix} 4D^{(n/2)} + D_{00}^{(2)}U^{(n/2)} & 4D^{(n/2)} + D_{01}^{(2)}U^{(n/2)} \\ 4D^{(n/2)} + D_{10}^{(2)}U^{(n/2)} & 4D^{(n/2)} + D_{11}^{(2)}U^{(n/2)} \end{bmatrix}. \tag{13.14}$$

Applying this relation to $D^{(2)}$ produces

$$D^{(4)} = \begin{bmatrix} 0 & 8 & 2 & 10 \\ 12 & 4 & 14 & 6 \\ 3 & 11 & 1 & 9 \\ 15 & 7 & 13 & 5 \end{bmatrix}. \tag{13.15}$$

The techniques presented thus far have assumed that the image array being shown is smaller than the display device's pixel array, so that multiple display pixels can be used for one

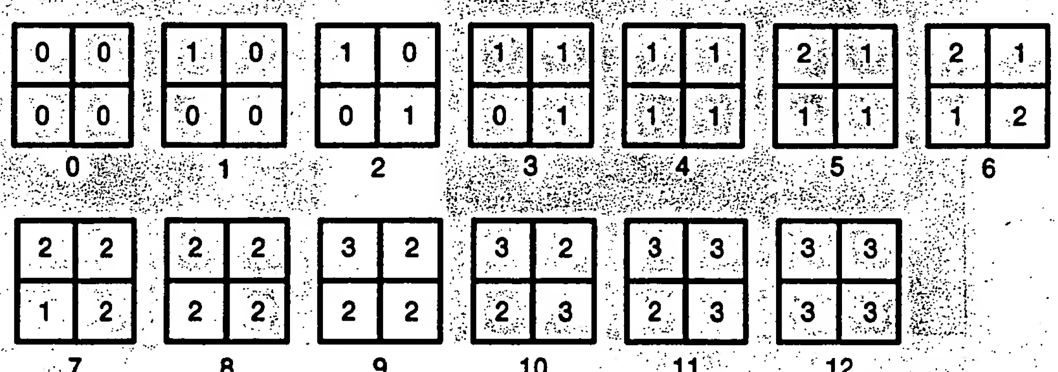

Fig. 13.13 Dither patterns for intensity levels 0 to 13 approximated using 2 × 2 patterns of pixels, with 2 bits (four intensity levels) per pixel. The intensities of the individual pixels sum to the intensity level for each pattern.

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image pixel. What if the image and display device arrays are the same size? A simple adaptation of the ordered-dither (either clustered-dot or dispersed-dot) approach can be used. Whether or not to intensify the pixel at point (x, y) depends on the desired intensity $S(x, y)$ at that point and on the dither matrix. To display the point at (x, y), we compute

$$i = x \text{ modulo } n, \qquad j = y \text{ modulo } n. \tag{13.16}$$

Then, if

$$S(x, y) > D_{ij}^{(n)}, \tag{13.17}$$

the point at (x, y) is intensified; otherwise, it is not. That is, 1 pixel in the image array controls 1 pixel in the display array. Notice that large areas of fixed image intensity are displayed exactly as when the image-array size is less than the display-array size, so the effect of equal image and display arrays is apparent only in areas where intensity varies.

Figure 13.14(a) is a face digitized at 512 × 512 and shown on a 512 × 512 bilevel display using $D^{(8)}$. Compare this bilevel result to the multilevel pictures shown earlier in this section. Further pictures displayed by means of ordered dither appear in [JARV76a; JARV76b; ULIC87], where more ways to display continuous-tone images on bilevel displays are described.

Error diffusion, another way to handle the case when the image and display array sizes are equal, was developed by Floyd and Steinberg [FLOY75]; its visual results are often satisfactory. The error (i.e., the difference between the exact pixel value and the approximated value actually displayed) is added to the values of the four image-array pixels to the right of and below the pixel in question: $\frac{7}{16}$ of the error to the pixel to the right, $\frac{3}{16}$ to the pixel below and to the left, $\frac{5}{16}$ to the pixel immediately below, and $\frac{1}{16}$ to the pixel below

(a)

(b)

Fig. 13.14 A continuous-tone photograph reproduced with (a) $D^{(8)}$ ordered dither, and (b) Floyd-Steinberg error diffusion. (Courtesy of Alan Paeth, University of Waterloo Computer Graphics Lab.)

and to the right. This has the effect of spreading, or diffusing, the error over several pixels in the image array. Figure 13.14(b) was created using this method.

Given a picture S to be displayed in the intensity matrix I, the modified values in S and the displayed values in I are computed for pixels in scan-line order, working downward from the topmost scanline.

```
K := Approximate(S[x, y]);        {Approximate S to nearest displayable intensity.}
I[x, y] := K;                     {Draw the pixel at (x, y).}
error := S[x, y] - K;             {Error term}
{Step 1: spread 7/16 of error into the pixel to the right, at (x + 1, y).}
S[x + 1, y] := S[x + 1, y] + 7 * error /16;
{Step 2: spread 3/16 of error into pixel below and to the left.}
S[x - 1, y - 1] := S[x - 1, y - 1] + 3 * error /16;
{Step 3: spread 5/16 of error into pixel below.}
S[x, y - 1] := S[x, y - 1] + 5 * error /16;
{Step 4: spread 1/16 of error below and to the right.}
S[x + 1, y - 1] := S[x + 1, y - 1] + error /16
```

To avoid introducing visual artifacts into the displayed image, we must ensure that the four errors sum exactly to *error*; no roundoff errors can be allowed. This can be done by calculating the step 4 error term as *error* minus the error terms from the first three steps. The function *Approximate* returns the displayable intensity value closest to the actual pixel value. For a bilevel display, the value of S is simply rounded to 0 or 1.

Even better results can be obtained by alternately scanning left to right and right to left; on a right-to-left scan, the left–right directions for errors in steps 1, 2, and 4 are reversed. For a detailed discussion of this and other error-diffusion methods, see [ULIC87]. Other approaches are discussed in [KNUT87].

Suppose the size of the image array is less than the size of the display array, the number of intensities in the image and display are equal, and we wish to display the image at the size of the display array. A simple case of this is an 8-bit-per-pixel, 512×512 image and an 8-bit-per-pixel, 1024×1024 display. If we simply replicate image pixels horizontally and vertically in the display array, the replicated pixels on the display will form squares that are quite obvious to the eye. To avoid this problem, we can interpolate intensities to calculate the pixel values. For instance, if an image S is to be displayed at double resolution, then the intensities I to display (with $x = 2x'$ and $y = 2y'$) are

$$
\begin{aligned}
I[x, y] &:= S[x', y'];\\
I[x + 1, y] &:= \tfrac{1}{2}(S[x', y'] + S[x' + 1, y']);\\
I[x, y + 1] &:= \tfrac{1}{2}(S[x', y'] + S[x', y' + 1]);\\
I[x + 1, y + 1] &:= \tfrac{1}{4}(S[x', y'] + S[x' + 1, y'] + S[x', y' + 1] + S[x' + 1, y' + 1]).
\end{aligned}
$$

See Section 17.4 for a discussion of two-pass scaling transformations of images, and Section 3.17 for a description of the filtering and image-reconstruction techniques that are applicable to this problem.

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13.2 CHROMATIC COLOR

The visual sensations caused by colored light are much richer than those caused by achromatic light. Discussions of color perception usually involve three quantities, known as hue, saturation, and lightness. *Hue* distinguishes among colors such as red, green, purple, and yellow. *Saturation* refers to how far color is from a gray of equal intensity. Red is highly saturated; pink is relatively unsaturated; royal blue is highly saturated; sky blue is relatively unsaturated. Pastel colors are relatively unsaturated; unsaturated colors include more white light than do the vivid, saturated colors. *Lightness* embodies the achromatic notion of perceived intensity of a reflecting object. *Brightness*, a fourth term, is used instead of lightness to refer to the perceived intensity of a self-luminous (i.e., emitting rather than reflecting light) object, such as a light bulb, the sun, or a CRT.

It is necessary to specify and measure colors if we are to use them precisely in computer graphics. For reflected light, we can do this by visually comparing a sample of unknown color against a set of "standard" samples. The unknown and sample colors must be viewed under a standard light source, since the perceived color of a surface depends both on the surface and on the light under which the surface is viewed. The widely used Munsell color-order system includes sets of published standard colors [MUNS76] organized in a 3D space of hue, value (what we have defined as lightness), and chroma (saturation). Each color is named, and is ordered so as to have an equal perceived "distance" in color space (as judged by many observers) from its neighbors. [KELL76] gives an extensive discussion of standard samples, charts depicting the Munsell space, and tables of color names.

In the printing industry and graphic design profession, colors are typically specified by matching to printed color samples. Color Plate I.33 is taken from a widely used color-matching system.

Artists often specify color as different tints, shades, and tones of strongly saturated, or pure, pigments. A *tint* results from adding white pigment to a pure pigment, thereby decreasing saturation. A *shade* comes from adding a black pigment to a pure pigment, thereby decreasing lightness. A *tone* is the consequence of adding both black and white pigments to a pure pigment. All these steps produce different colors of the same hue, with varying saturation and lightness. Mixing just black and white pigments creates grays. Figure 13.15 shows the relationship of tints, shades, and tones. The percentage of pigments that must be mixed to match a color can be used as a color specification. The Ostwald [OSTW31] color-order system is similar to the artist's model.

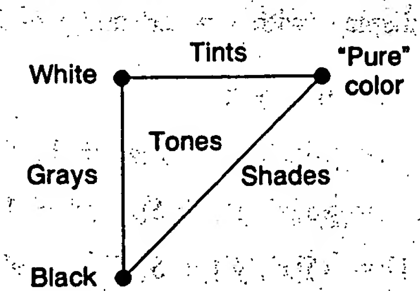

Fig. 13.15 Tints, tones, and shades.

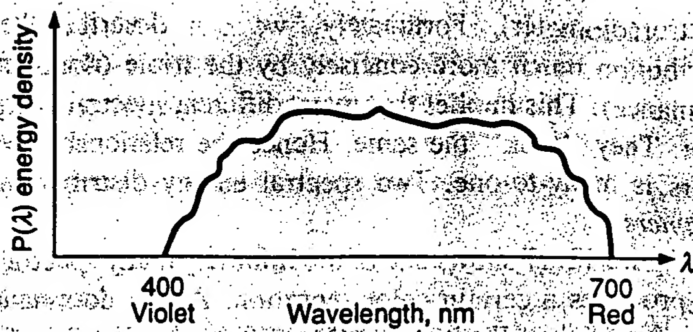

Fig. 13.16 Typical spectral energy distribution $P(\lambda)$ of a light.

13.2.1 Psychophysics

The Munsell and artists' pigment-mixing methods are subjective: They depend on human observers' judgments, the lighting, the size of the sample, the surrounding color, and the overall lightness of the environment. An objective, quantitative way of specifying colors is needed, and for this we turn to the branch of physics known as *colorimetry*. Important terms in colorimetry are dominant wavelength, excitation purity, and luminance.

Dominant wavelength is the wavelength of the color we "see" when viewing the light, and corresponds to the perceptual notion of hue[2]; *excitation purity* corresponds to the saturation of the color; *luminance* is the amount or intensity of light. The excitation purity of a colored light is the proportion of pure light of the dominant wavelength and of white light needed to define the color. A completely pure color is 100 percent saturated and thus contains no white light, whereas mixtures of a pure color and white light have saturations somewhere between 0 and 100 percent. White light and hence grays are 0 percent saturated, containing no color of any dominant wavelength. The correspondences between these perceptual and colorimetry terms are as follows:

Perceptual term	**Colorimetry**
Hue	Dominant wavelength
Saturation	Excitation purity
Lightness (reflecting objects)	Luminance
Brightness (self-luminous objects)	Luminance

Fundamentally, light is electromagnetic energy in the 400- to 700-nm wavelength part of the spectrum, which is perceived as the colors from violet through indigo, blue, green, yellow, and orange to red. Color Plate I.34 shows the colors of the spectrum. The amount of energy present at each wavelength is represented by a spectral energy distribution $P(\lambda)$, such as shown in Fig. 13.16 and Color Plate I.34. The distribution represents an infinity of numbers, one for each wavelength in the visible spectrum (in practice, the distribution is represented by a large number of sample points on the spectrum, as measured by a

[2]Some colors, such as purple, have no true dominant wavelength, as we shall see later.

spectroradiometer). Fortunately, we can describe the visual effect of any spectral distribution much more concisely by the triple (dominant wavelength, excitation purity, luminance). This implies that many different spectral energy distributions produce the same color: They "look" the same. Hence the relationship between spectral distributions and colors is many-to-one. Two spectral energy distributions that look the same are called *metamers*.

Figure 13.17 shows one of the infinitely many spectral distributions $P(\lambda)$, or metamers, that produces a certain color sensation. At the dominant wavelength, there is a spike of energy of level e_2. White light, the uniform distribution of energy at level e_1, is also present. The excitation purity depends on the relation between e_1 and e_2: when $e_1 = e_2$, excitation purity is 0 percent; when $e_1 = 0$, excitation purity is 100 percent. Brightness, which is proportional to the integral of the product of the curve and the luminous efficiency function (defined later), depends on both e_1 and e_2. In general, spectral distributions may be more complex than the one shown, and it is not possible to determine the dominant wavelength merely by looking at the spectral distributions. In particular, the dominant wavelength may *not* be the one whose component in the spectral distribution is largest.

How does this discussion relate to the red, green, and blue phosphor dots on a color CRT? And how does it relate to the *tristimulus theory* of color perception, which is based on the hypothesis that the retina has three kinds of color sensors (called cones), with peak sensitivity to red, green, or blue lights? Experiments based on this hypothesis produce the spectral-response functions of Fig. 13.18. The peak blue response is around 440 nm; that for green is about 545 nm; that for red is about 580 nm. (The terms "red" and "green" are somewhat misleading here, as the 545 nm and 580 nm peaks are actually in the yellow range.) The curves suggest that the eye's response to blue light is much less strong than is its response to red or green.

Figure 13.19 shows the *luminous-efficiency function*, the eye's response to light of constant luminance, as the dominant wavelength is varied: our peak sensitivity is to yellow-green light of wavelength around 550 nm. There is experimental evidence that this curve is just the sum of the three curves shown in Fig. 13.18.

The tristimulus theory is intuitively attractive because it corresponds loosely to the notion that colors can be specified by positively weighted sums of red, green, and blue (the so-called primary colors). This notion is almost true: The three color-matching functions in

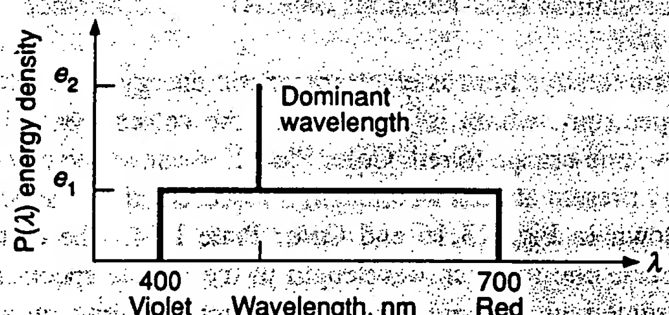

Fig. 13.17 Spectral energy distribution, $P(\lambda)$, illustrating dominant wavelength, excitation purity, and luminance.

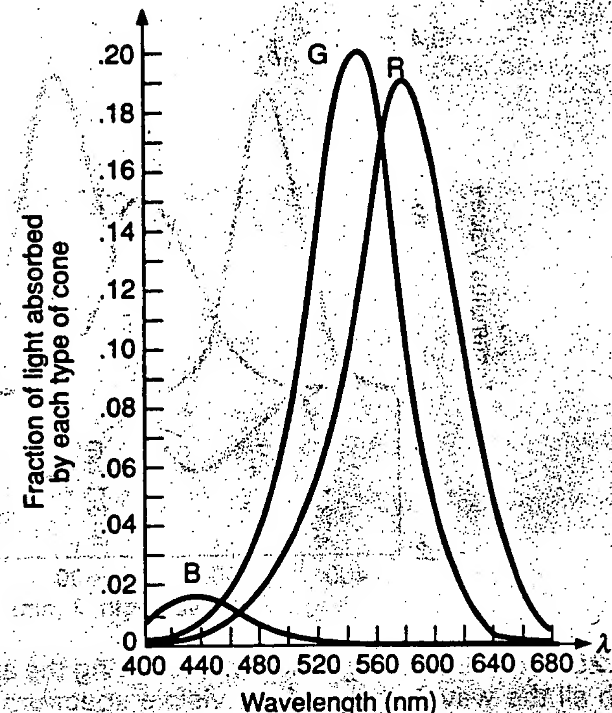

Fig. 13.18 Spectral-response functions of each of the three types of cones on the human retina.

Fig. 13.20 show the amounts of red, green, and blue light needed by an average observer to match a color of constant luminance, for all values of dominant wavelength in the visible spectrum.

A negative value in Fig. 13.20 means that we cannot match the color by adding together the primaries. However, if one of the primaries is added to the color sample, the sample can then be matched by a mixture of the other two primaries. Hence, negative values in Fig. 13.20 indicate that the primary was added to the color being matched. The need for negative values does not mean that the notion of mixing red, green, and blue to obtain other

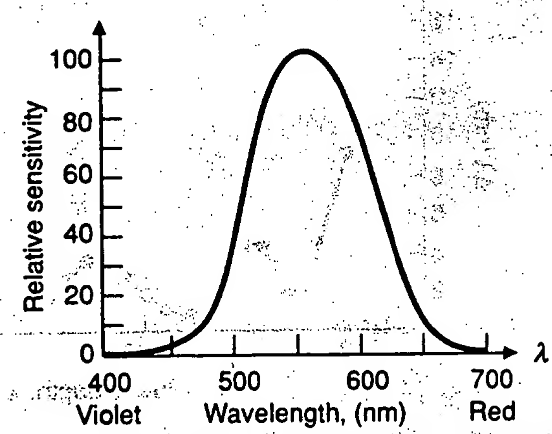

Fig. 13.19 Luminous-efficiency function for the human eye.

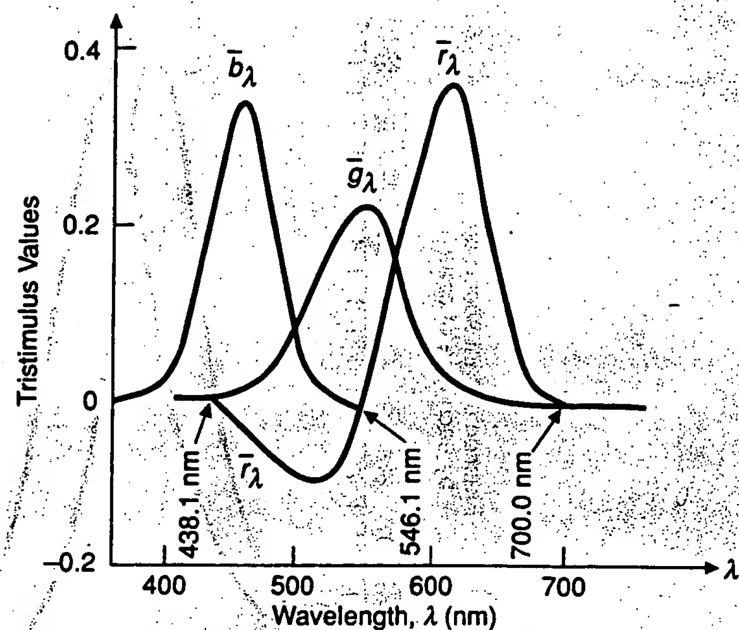

Fig. 13.20 Color-matching functions, showing the amounts of three primaries needed to match all the wavelengths of the visible spectrum.

colors is invalid; on the contrary, a huge range of colors can be matched by positive amounts of red, green, and blue. Otherwise, the color CRT would not work! It does mean, however, that certain colors cannot be produced by RGB mixes, and hence cannot be shown on an ordinary CRT.

The human eye can distinguish hundreds of thousands of different colors in color space, when different colors are judged side by side by different viewers who state whether the colors are the same or different. As shown in Fig. 13.21, when colors differ only in hue, the wavelength between just noticably different colors varies from more than 10 nm at the extremes of the spectrum to less than 2 nm around 480 nm (blue) and 580 nm (yellow).

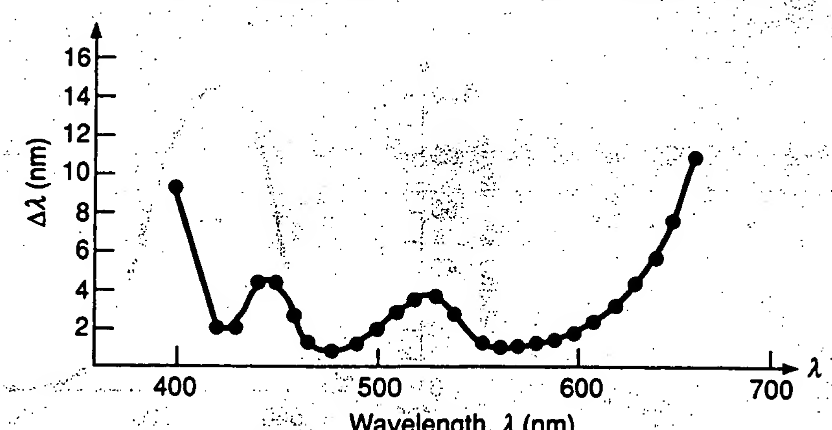

Fig. 13.21 Just-noticable color differences as a function of wavelength λ. The ordinate indicates the minimum detectable difference in wavelength between adjacent color samples. (Source: Data are from [BEDF58].)

Except at the spectrum extremes, however, most distinguished hues are within 4 nm. Altogether about 128 fully saturated hues can be distinguished.

The eye is less sensitive to hue changes in less saturated light. This is not surprising: As saturation tends to 0 percent, all hues tend to white. Sensitivity to changes in saturation for a fixed hue and lightness is greater at the extremes of the visible spectrum, where about 23 distinguishable steps exist. Around 575 nm, only 16 saturation steps can be distinguished [JONE26].

13.2.2 The CIE Chromaticity Diagram

Matching and therefore defining a colored light with a mixture of three fixed primaries is a desirable approach to specifying color, but the need for negative weights suggested by Fig. 13.20 is awkward. In 1931, the *Commission Internationale de l'Éclairage (CIE)* defined three standard primaries, called **X**, **Y**, and **Z**, to replace red, green, and blue in this matching process. The three corresponding color-matching functions, $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, are shown in Fig. 13.22. The primaries can be used to match, with only positive weights, all the colors we can see. The **Y** primary was intentionally defined to have a color-matching function $\bar{y}_\lambda$ that exactly matches the luminous-efficiency function of Fig. 13.19. Note that $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ are not the spectral distributions of the **X**, **Y**, and **Z** colors, just as the curves in Fig. 13.20 are not the spectral distributions of red, green, and blue. They are merely auxilliary functions used to compute how much of **X**, **Y**, and **Z** should be mixed together to generate a metamer of any visible color.

The color-matching functions are defined tabularly at 1-nm intervals, and are found in texts such as [WYSZ82; BILL81]. The distributions were defined for color samples that

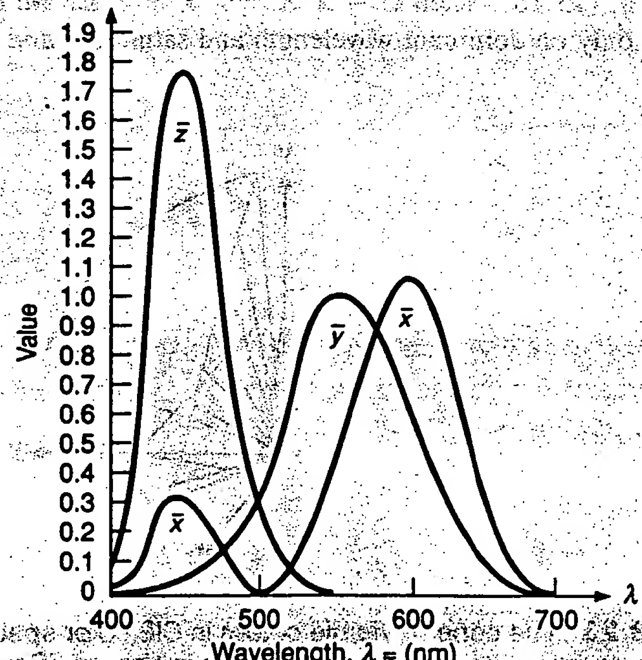

Fig. 13.22 The color-matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, for the 1931 CIE **X**, **Y**, **Z** primaries.

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subtend a 2° field of view on the retina. The original 1931 tabulation is normally used in work relevant to computer graphics. A later 1964 tabulation for a 10° field of view is not generally useful, because it emphasizes larger areas of constant color than are normally found in graphics.

The three CIE color-matching functions are linear combinations of the color-matching functions from Fig. 13.20. This means that the definition of a color with red, green, and blue lights can be converted via a linear transformation into its definition with the CIE primaries, and vice versa.

The amounts of **X**, **Y**, and **Z** primaries needed to match a color with a spectral energy distribution $P(\lambda)$, are:

$$X = k \int P(\lambda)\, \bar{x}_\lambda\, d\lambda, \quad Y = k \int P(\lambda)\, \bar{y}_\lambda\, d\lambda, \quad Z = k \int P(\lambda)\, \bar{z}_\lambda\, d\lambda. \tag{13.18}$$

For self-luminous objects like a CRT, k is 680 lumens/watt. For reflecting objects, k is usually selected such that bright white has a Y value of 100; then other Y values will be in the range of 0 to 100. Thus,

$$k = \frac{100}{\int P_w(\lambda)\bar{y}_\lambda\, d\lambda} \tag{13.19}$$

where $P_w(\lambda)$ is the spectral energy distribution for whatever light source is chosen as the standard for white. In practice, these integrations are performed by summation, as none of the energy distributions are expressed analytically.

Figure 13.23 shows the cone-shaped volume of XYZ space that contains visible colors. The volume extends out from the origin into the postive octant, and is capped at the smooth curved line terminating the cone.

Let (X, Y, Z) be the weights applied to the CIE primaries to match a color **C**, as found using Eq. (13.18). Then $\mathbf{C} = X\,\mathbf{X} + Y\,\mathbf{Y} + Z\,\mathbf{Z}$. We define *chromaticity* values (which depend only on dominant wavelength and saturation and are independent of the amount of

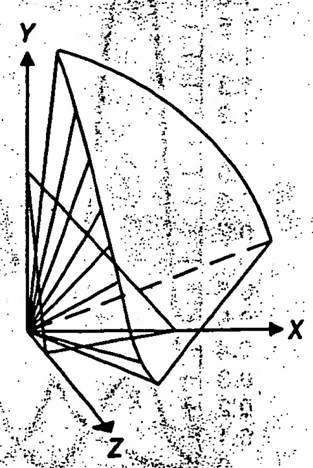

Fig. 13.23 The cone of visible colors in CIE color space is shown by the lines radiating from the origin. The $X + Y + Z = 1$ plane is shown. (Courtesy of Gary Meyer, Program of Computer Graphics, Cornell University, 1978.)

luminous energy) by normalizing against $X + Y + Z$, which can be thought of as the total amount of light energy:

$$x = \frac{X}{(X + Y + Z)},\ y = \frac{Y}{(X + Y + Z)},\ z = \frac{Z}{(X + Y + Z)}. \tag{13.20}$$

Notice that $x + y + z = 1$. That is, x, y, and z are on the $(X + Y + Z = 1)$ plane of Fig. 13.23. Color plate II.1 shows the $X + Y + Z = 1$ plane as part of CIE space, and also shows an orthographic view of the plane along with the projection of the plane onto the (X, Y) plane. This latter projection is just the CIE chromaticity diagram.

If we specify x and y, then z is determined by $z = 1 - x - y$. We cannot recover X, Y, and Z from x and y, however. To recover them, we need one more piece of information, typically Y, which carries luminance information. Given (x, y, Y), the transformation to the corresponding (X, Y, Z) is

$$X = \frac{x}{y}Y, \quad Y = Y, Z = \frac{1 - x - y}{y}Y. \tag{13.21}$$

Chromaticity values depend only on dominant wavelength and saturation and are independent of the amount of luminous energy. By plotting x and y for all visible colors, we obtain the CIE chromaticity diagram shown in Fig. 13.24, which is the projection onto the (X, Y) plane of the $(X + Y + Z = 1)$ plane of Fig. 13.23. The interior and boundary of the horseshoe-shaped region represent all visible chromaticity values. (All perceivable colors with the same chromaticity but different luminances map into the same point within this region.) The 100 percent spectrally pure colors of the spectrum are on the curved part of the boundary. A standard white light, meant to approximate sunlight, is formally defined by a

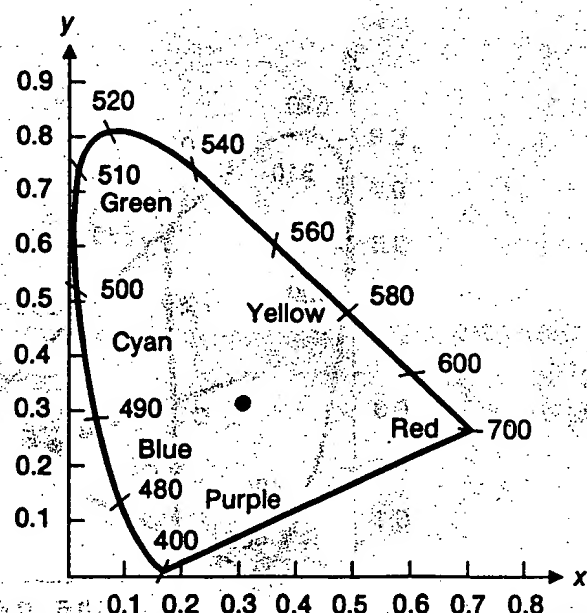

Fig. 13.24 The CIE chromaticity diagram. Wavelengths around the periphery are in nanometers. The dot marks the position of illuminant C.

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light source *illuminant C*, marked by the center dot. It is near but not at the point where $x = y = z = \frac{1}{3}$. Illuminant C was defined by specifying a spectral power distribution that is close to daylight at a correlated color temperature of 6774° Kelvin.

The CIE chromaticity diagram is useful in many ways. For one, it allows us to measure the dominant wavelength and excitation purity of any color by matching the color with a mixture of the three CIE primaries. (Instruments called *colorimeters* measure tristimulus X, Y, and Z values, from which chromaticity coordinates are computed using Eq. (13.20). *Spectroradiometers* measure both the spectral energy distribution and the tristimulus values.) Now suppose the matched color is at point A in Fig. 13.25. When two colors are added together, the new color lies somewhere on the straight line in the chromaticity diagram connecting the two colors being added. Therefore, color A can be thought of as a mixture of "standard" white light (illuminant C) and the pure spectral light at point B. Thus, B defines the dominant wavelength. The ratio of length AC to length BC, expressed as a percentage, is the excitation purity of A. The closer A is to C, the more white light A includes and the less pure it is.

The chromaticity diagram factors out luminance, so color sensations that are luminance-related are excluded. For instance, brown, which is an orange-red chromaticity at very low luminance relative to its surrounding area, does not appear. It is thus important to remember that the chromaticity diagram is not a full color palette. There is an infinity of planes in (X, Y, Z) space, each of which projects onto the chromaticity diagram and each of which loses luminance information in the process. The colors found on each such plane are all different.

Complementary colors are those that can be mixed to produce white light (such as D and E in Fig. 13.25). Some colors (such as F in Fig. 13.25) cannot be defined by a

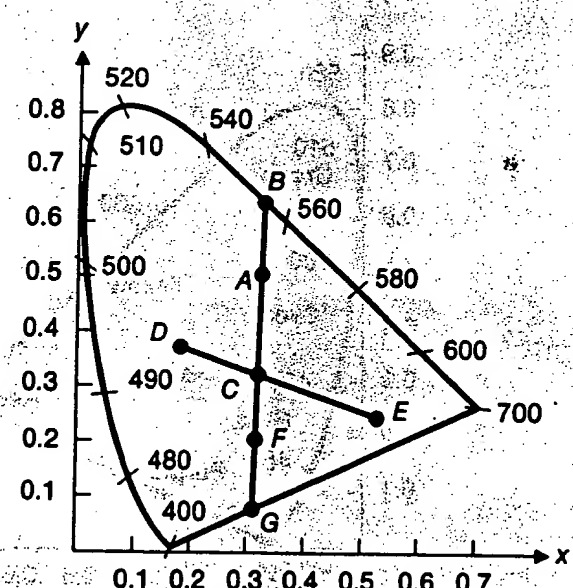

Fig. 13.25 Colors on the chromaticity diagram. The dominant wavelength of color *A* is that of color *B*. Colors *D* and *E* are complementary colors. The dominant wavelength of color *F* is defined as the complement of the dominant wavelength of color *A*.

dominant wavelength and are thus called *nonspectral*. In this case, the dominant wavelength is said to be the complement of the wavelength at which the line through F and C intersects the horseshoe part of the curve at point B, and is designated by a "c" (here about 555 nm c). The excitation purity is still defined by the ratio of lengths (here CF to CG). The colors that must be expressed by using a complementary dominant wavelength are the purples and magentas; they occur in the lower part of the CIE diagram. Complementary colors still can be made to fit the dominant wavelength model of Fig. 13.17, in the sense that if we take a flat spectral distribution and delete some of the light at frequency B, the resulting color will be perceived as F.

Another use of the CIE chromaticity diagram is to define *color gamuts*, or color ranges, that show the effect of adding colors together. Any two colors, say I and J in Fig. 13.26, can be added to produce any color along their connecting line by varying the relative amounts of the two colors being added. A third color K (see Fig. 13.26) can be used with various mixtures of I and J to produce the gamut of all colors in triangle IJK, again by varying relative amounts. The shape of the diagram shows why visible red, green, and blue cannot be additively mixed to match all colors: No triangle whose vertices are within the visible area can completely cover the visible area.

The chromaticity diagram is also used to compare the gamuts available on various color display and hardcopy devices. Color Plate II.2 shows the gamuts for a color television monitor, film, and print. The chromaticity coordinates for the phosphors in two typical monitors are these:

	Short-persistence phosphors			Long-persistence phosphors		
	Red	Green	Blue	Red	Green	Blue
x	0.61	0.29	0.15	0.62	0.21	0.15
y	0.35	0.59	0.063	0.33	0.685	0.063

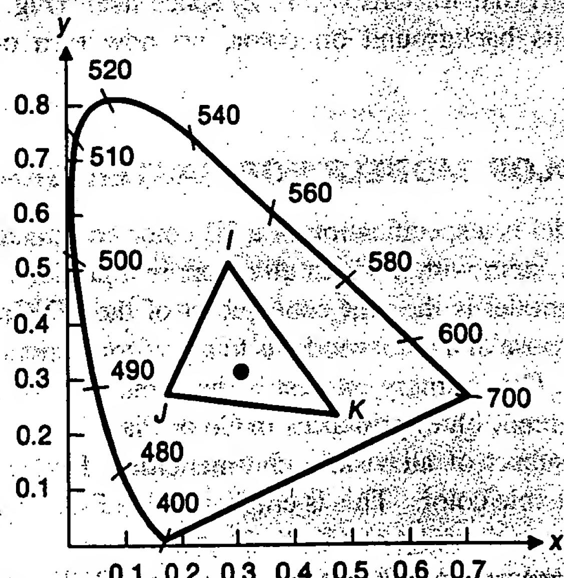

Fig. 13.26 Mixing colors. All colors on the line IJ can be created by mixing colors I and J; all colors in the triangle IJK can be created by mixing colors I, J, and K.

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The smallness of the print gamut with respect to the color-monitor gamut suggests that, if images originally seen on a monitor must be faithfully reproduced by printing, a reduced gamut of colors should be used with the monitor. Otherwise, accurate reproduction will not be possible. If, however, the goal is to make a pleasing rather than an exact reproduction, small differences in color gamuts are less important. A discussion of color-gamut compression can be found in [HALL89].

There is a problem with the CIE system. Consider the distance from color $C_1 = (X_1, Y_1, Z_1)$ to color $C_1 + \Delta C$, and the distance from color $C_2 = (X_2, Y_2, Z_2)$ to color $C_2 + \Delta C$, where $\Delta C = (\Delta X, \Delta Y, \Delta Z)$. Both distances are equal to ΔC, yet in general they will not be perceived as being equal. This is because of the variation, throughout the spectrum, of the just noticable differences discussed in Section 13.2.1. A *perceptually uniform* color space is needed, in which two colors that are equally distant are *perceived* as equally distant by viewers.

The 1976 CIE LUV uniform color space was developed in response to this need. With (X_n, Y_n, Z_n) as the coordinates of the color that is to be defined as white, the space is defined by

$$L^* = 116\,(Y/Y_n)^{1/3} - 16,\; Y/Y_n > 0.01$$
$$u^* = 13\,L^*\,(u' - u'_n),$$
$$v^* = 13\,L^*\,(v' - v'_n),$$
$$u' = \frac{4X}{X + 15Y + 3Z},\quad v' = \frac{9Y}{X + 15Y + 3Z}, \tag{13.22}$$
$$u'_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n},\quad v'_n = \frac{9Y_n}{X_n + 15Y_n + 3Z_n}.$$

The shape of the 3D volume of visible colors defined by these equations is of course different from that for CIE (X, Y, Z) space itself (Fig. 13.23).

With this background on color, we now turn our attention to color in computer graphics.

13.3 COLOR MODELS FOR RASTER GRAPHICS

A color model is a specification of a 3D color coordinate system and a visible subset in the coordinate system within which all colors in a particular color gamut lie. For instance, the RGB color model is the unit cube subset of the 3D Cartesian coordinate system.

The purpose of a color model is to allow convenient specification of colors within some color gamut. Our primary interest is the gamut for color CRT monitors, as defined by the RGB (red, green, blue) primaries in Color Plate II.2. As we see in this color plate, a color gamut is a subset of all visible chromaticities. Hence, a color model cannot be used to specify all visible colors. This is emphasized in Fig. 13.27, which shows that the gamut of a CRT monitor is a subset of (X, Y, Z) space.

Three hardware-oriented color models are RGB, used with color CRT monitors, YIQ, the broadcast TV color system, and CMY (cyan, magenta, yellow) for some color-printing devices. Unfortunately, none of these models are particularly easy to use, because they do not relate directly to intuitive color notions of hue, saturation, and brightness. Therefore,

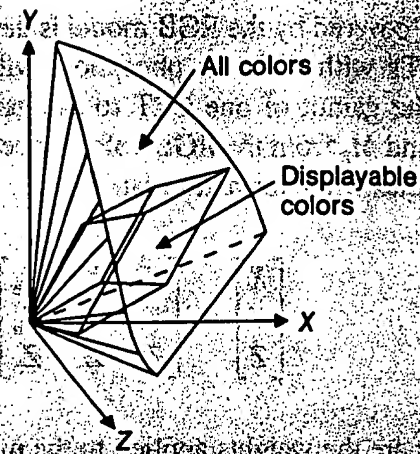

Fig. 13.27 The color gamut for a typical color monitor within the CIE color space. The range of colors that can be displayed on the monitor is clearly smaller than that of all colors visible in CIE space. (Courtesy of Gary Meyer, Program of Computer Graphics, Cornell University, 1978.)

another class of models has been developed with ease of use as a goal. Several such models are described in [GSPC79; JOBL78; MEYE80; SMIT78]. We discuss three, the HSV (sometimes called HSB), HLS, and HVC models.

With each model is given a means of converting to some other specification. For RGB, this conversion is to CIE's (X, Y, Z) space. This conversion is important, because CIE is the worldwide standard. For all of the other models, the conversion is to RGB; hence, we can convert from, say, HSV to RGB to the CIE standard.

13.3.1 The RGB Color Model

The red, green, and blue (RGB) color model used in color CRT monitors and color raster graphics employs a Cartesian coordinate system. The RGB primaries are *additive* primaries; that is, the individual contributions of each primary are added together to yield the result, as suggested in Color Plate II.3. The subset of interest is the unit cube shown in Fig. 13.28. The main diagonal of the cube, with equal amounts of each primary, represents the gray levels: black is (0, 0, 0); white is (1, 1, 1). Color Plates II.4 and II.5 show several views of the RGB color model.

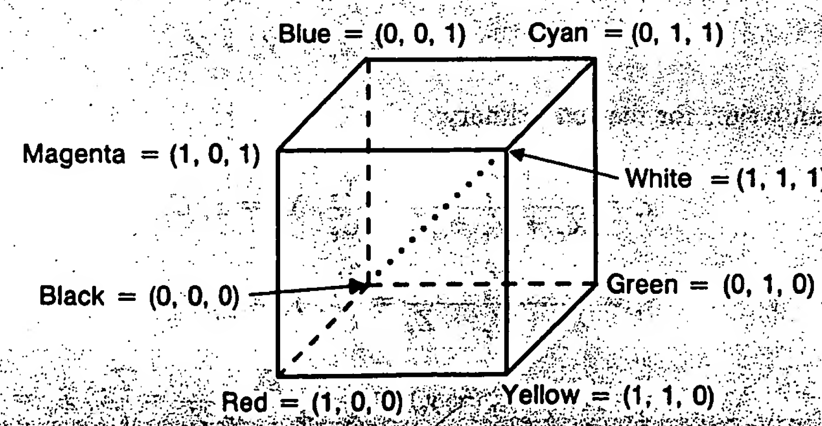

Fig. 13.28 The RGB cube. Grays are on the dotted main diagonal.

The color gamut covered by the RGB model is defined by the chromaticities of a CRT's phosphors. Two CRTs with different phosphors will cover different gamuts. To convert colors specified in the gamut of one CRT to the gamut of another CRT, we can use the transformations M_1 and M_2 from the RGB color space of each monitor to the (X, Y, Z) color space. The form of each transformation is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \tag{13.23}$$

where X_r, X_g, and X_b are the weights applied to the monitor's RGB colors to find X, and so on.

Defining M as the 3×3 matrix of color-matching coefficients, we write Eq. (13.23) as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{13.24}$$

With M_1 and M_2 the matricies that convert from each of the two monitor's gamuts to CIE, $M_2^{-1}M_1$ converts from the RGB of monitor 1 to the RGB of monitor 2. This matrix product is all that is needed if the color in question lies in the gamuts of both monitors. What if a color C_1 is in the gamut of monitor 1 but is not in the gamut of monitor 2? The corresponding color $C_2 = M_2^{-1}M_1C_1$ will be outside the unit cube and hence will not be displayable. A simple but not very satisfactory solution is to clamp the color values—that is, to replace values of R, G, or B that are less than 0 with 0, and values that are greater than 1 with 1. More satisfactory but also more complex approaches are described in [HALL89].

The chromaticity coordinates for the RGB phosphors are usually available from CRT manufacturers' specifications. If not, a colorimeter can also be used to measure the chromaticity coordinates directly, or a spectroradiometer can be used to measure $P(\lambda)$, which can then be converted to chromaticity coordinates using Eqs. (13.18), (13.19), and (13.20). Denoting the coordinates by (x_r, y_r) for red, (x_g, y_g) for green, and (x_b, y_b) for blue, and defining C_r as

$$C_r = X_r + Y_r + Z_r, \tag{13.25}$$

we can write, for the red primary;

$$x_r = \frac{X_r}{X_r + Y_r + Z_r} = \frac{X_r}{C_r},\ X_r = x_r\,C_r,$$

$$y_r = \frac{Y_r}{X_r + Y_r + Z_r} = \frac{Y_r}{C_r},\ Y_r = y_r\,C_r,$$

$$z_r = (1 - x_r - y_r) = \frac{Z_r}{X_r + Y_r + Z_r} = \frac{Z_r}{C_r},\ Z_r = z_r\,C_r. \tag{13.26}$$

With similar definitions for C_g and C_b, Eq. (13.23) can be rewritten as:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_r C_r & x_g C_g & x_b C_b \\ y_r C_r & y_g C_g & y_b C_b \\ (1 - x_r - y_r)C_r & (1 - x_g - y_g)C_g & (1 - x_b - y_b)C_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \quad (13.27)$$

The unknowns C_r, C_g, and C_b can be found in one of two ways [MEYE83]. First, the luminances Y_r, Y_g, and Y_b of maximum-brightness red, green, and blue may be known or can be measured with a high-quality photometer (inexpensive meters can be off by factors of 2 to 10 on the blue reading). These measured luminances can be combined with the known y_r, y_g, and y_b to yield

$$C_r = Y_r/y_r,\ C_g = Y_g/y_g,\ C_b = Y_b/y_b. \quad (13.28)$$

These values are then substituted into Eq. (13.27), and the conversion matrix M is thus expressed in terms of the known quantities (x_r, y_r), (x_g, y_g), (x_b, y_b), Y_r, Y_g, and Y_b.

We can also remove the unknown variables from Eq. (13.27) if we know or can measure the X_w, Y_w, and Z_w for the white color produced when $R = G = B = 1$. For this case, Eq. (13.27) can be rewritten as

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ (1 - x_r - y_r) & (1 - x_g - y_g) & (1 - x_b - y_b) \end{bmatrix} \begin{bmatrix} C_r \\ C_g \\ C_b \end{bmatrix}, \quad (13.29)$$

solved for C_r, C_g, and C_b (the only unknowns), and the resulting values substituted into Eq. (13.27). Alternatively, it may be that the white color is given by x_w, y_w, and Y_w; in this case, before solving Eq. (13.29), we first find

$$X_w = x_w \frac{Y_w}{y_w},\ Z_w = z_w \frac{Y_w}{y_w}. \quad (13.30)$$

13.3.2 The CMY Color Model

Cyan, magenta, and yellow are the complements of red, green, and blue, respectively. When used as filters to subtract color from white light, they are called *subtractive primaries*. The subset of the Cartesian coordinate system for the CMY model is the same as that for RGB except that white (full light) instead of black (no light) is at the origin. Colors are specified by what is removed or subtracted from white light, rather than by what is added to blackness.

A knowledge of CMY is important when dealing with hardcopy devices that deposit colored pigments onto paper, such as electrostatic and ink-jet plotters. When a surface is coated with cyan ink, no red light is reflected from the surface. Cyan subtracts red from the reflected white light, which is itself the sum of red, green, and blue. Hence, in terms of the

additive primaries, cyan is white minus red, that is, blue plus green. Similarly, magenta absorbs green, so it is red plus blue; yellow absorbs blue, so it is red plus green. A surface coated with cyan and yellow absorbs red and blue, leaving only green to be reflected from illuminating white light. A cyan, yellow, and magenta surface absorbs red, green, and blue, and therefore is black. These relations, diagrammed in Fig. 13.29, can be seen in Color Plate II.6 and are represented by the following equation:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{13.31}$$

The unit column vector is the RGB representation for white and the CMY representation for black.

The conversion from RGB to CMY is then

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}. \tag{13.32}$$

These straightforward transformations can be used for converting the eight colors that can be achieved with binary combinations of red, green, and blue into the eight colors achievable with binary combinations of cyan, magenta, and yellow. This conversion is relevant for use on ink-jet and xerographic color printers.

Another color model, CMYK, uses black (abbreviated as K) as a fourth color. CMYK is used in the four-color printing process of printing presses and some hard-copy devices.

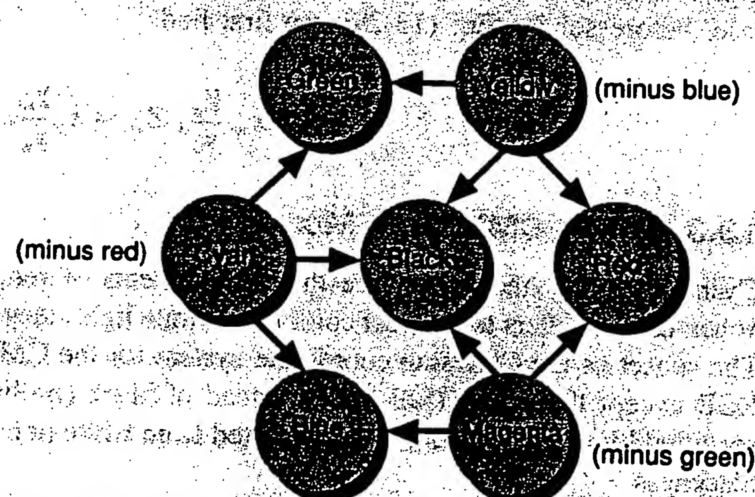

Fig. 13.29 Subtractive primaries (cyan, magenta, yellow) and their mixtures. For instance, cyan and yellow combine to green.

Given a CMY specification, black is used in place of equal amounts of C, M, and Y, according to the relations:

$$
\begin{aligned}
K &:= \min(C, M, Y) \\
C &:= C - K \\
M &:= M - K \\
Y &:= Y - K
\end{aligned}
\tag{13.34}
$$

This is discussed further in Section 13.4 and in [STON88].

13.3.3 The YIQ Color Model

The YIQ model is used in U.S. commercial color television broadcasting and is therefore closely related to color raster graphics. YIQ is a recoding of RGB for transmission efficiency and for downward compatibility with black-and-white television. The recoded signal is transmitted using the National Television System Committee (NTSC) [PRIT77] system.

The Y component of YIQ is not yellow but luminance, and is defined to be the same as the CIE Y primary. Only the Y component of a color TV signal is shown on black-and-white televisions: the chromaticity is encoded in I and Q. The YIQ model uses a 3D Cartesian coordinate system, with the visible subset being a convex polyhedron that maps into the RGB cube.

The RGB-to-YIQ mapping is defined as follows:

$$
\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
\tag{13.33}
$$

The quantities in the first row reflect the relative importance of green and red and the relative unimportance of blue in brightness. The inverse of the RGB-to-YIQ matrix is used for the YIQ-to-RGB conversion.

Equation (13.33) assumes that the RGB color specification is based on the standard NTSC RGB phosphor, whose CIE coordinates are

	Red	**Green**	**Blue**
x	0.67	0.21	0.14
y	0.33	0.71	0.08

and for which the white point, illuminant C, is $x_w = 0.31$, $y_w = 0.316$, and $Y_w = 100.0$.

Specifying colors with the YIQ model solves a potential problem with material being prepared for broadcast television: Two different colors shown side by side on a color monitor will appear to be different, but, when converted to YIQ and viewed on a monochrome monitor, they may appear to be the same. This problem can be avoided by

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specifying the two colors with different Y values in the YIQ color model space (i.e., by adjusting only the Y value to disambiguate them).

The YIQ model exploits two useful properties of our visual system. First, the system is more sensitive to changes in luminance than to changes in hue or saturation; that is, our ability to discriminate spatially color information is weaker than our ability to discriminate spatially monochrome information. This suggests that more bits of bandwidth should be used to represent Y than are used to represent I and Q, so as to provide higher resolution in Y. Second, objects that cover a very small part of our field of view produce a limited color sensation, which can be specified adequately with one rather than two color dimensions. This suggests that either I or Q can have a lower bandwidth than the other. The NTSC encoding of YIQ into a broadcast signal uses these properties to maximize the amount of information transmitted in a fixed bandwidth: 4 MHz is assigned to Y, 1.5 to I, and 0.6 to Q. Further discussion of YIQ can be found in [SMIT78; PRIT77].

13.3.4 The HSV Color Model

The RGB, CMY, and YIQ models are hardware-oriented. By contrast, Smith's HSV (hue, saturation, value) model [SMIT78] (also called the HSB model, with B for brightness) is user-oriented, being based on the intuitive appeal of the artist's tint, shade, and tone. The coordinate system is cylindrical, and the subset of the space within which the model is defined is a hexcone, or six-sided pyramid, as in Fig. 13.30. The top of the hexcone corresponds to $V = 1$, which contains the relatively bright colors. The colors of the $V = 1$ plane are *not* all of the same perceived brightness, however. Color Plates II.7 and II.8 show the color model.

Hue, or H, is measured by the angle around the vertical axis, with red at 0°, green at 120°, and so on (see Fig. 13.30). Complementary colors in the HSV hexcone are 180°

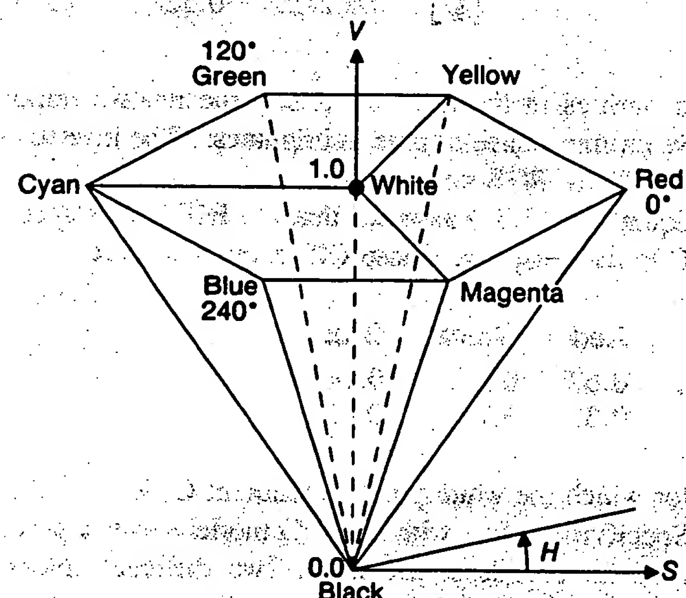

Fig. 13.30 Single-hexcone HSV color model. The $V = 1$ plane contains the RGB model's $R = 1$, $G = 1$, and $B = 1$ planes in the regions shown.

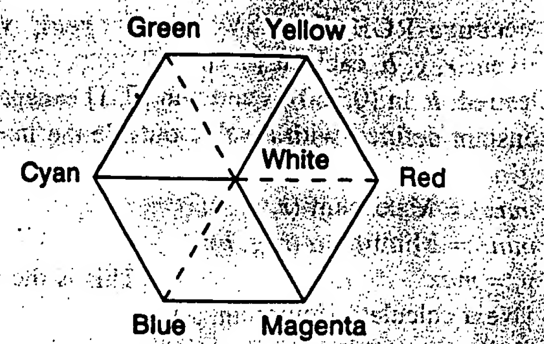

Fig. 13.31 RGB color cube viewed along the principal diagonal. Visible edges of the cube are solid; invisible edges are dashed.

opposite one another. The value of S is a ratio ranging from 0 on the center line (V axis) to 1 on the triangular sides of the hexcone. Saturation is measured relative to the color gamut represented by the model, which is, of course, a subset of the entire CIE chromaticity diagram. Therefore, saturation of 100 percent in the model is less than 100 percent excitation purity.

The hexcone is one unit high in V, with the apex at the origin. The point at the apex is black and has a V coordinate of 0. At this point, the values of H and S are irrelevant. The point $S = 0$, $V = 1$ is white. Intermediate values of V for $S = 0$ (on the center line) are the grays. When $S = 0$, the value of H is irrelevant (called by convention UNDEFINED). When S is not zero, H is relevant. For example, pure red is at $H = 0$, $S = 1$, $V = 1$. Indeed, any color with $V = 1$, $S = 1$ is akin to an artist's pure pigment used as the starting point in mixing colors. Adding white pigment corresponds to decreasing S (without changing V). Shades are created by keeping $S = 1$ and decreasing V. Tones are created by decreasing both S and V. Of course, changing H corresponds to selecting the pure pigment with which to start. Thus, H, S, and V correspond to concepts from the artists' color system, and are not exactly the same as the similar terms introduced in Section 13.2.

The top of the HSV hexcone corresponds to the projection seen by looking along the principal diagonal of the RGB color cube from white toward black, as shown in Fig. 13.31. The RGB cube has subcubes, as illustrated in Fig. 13.32. Each subcube, when viewed along

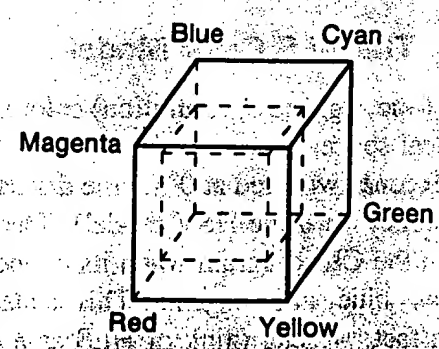

Fig. 13.32 RGB cube and a subcube.

```
procedure RGB_To_HSV (r, g, b : real; var h, s, v : real)
{Given: r, g, b, each in [0,1].
 Desired: h in [0,360), s and v in [0, 1] except if s = 0, then h = UNDEFINED, which is some
 constant defined with a value outside the interval [0,360].}
begin
  max := Maximum (r, g, b);
  min := Mimimum (r, g, b);
  v := max                      {This is the value v.}
  {Next calculate saturation, s.}
  if max <> 0 then
    s := (max - min)/max        {s is the saturation.}
  else s := 0                   {Saturation is 0 if red, green and blue are all 0}
  if s = 0 then
    h := UNDEFINED
  else                          {Chromatic case:  Saturation is not 0, so determine hue}
    begin
      delta := max - min
      if r = max then
        h := (g - b)/delta      {Resulting color is between yellow and magenta}
      else if g = max then
        h := 2 + (b - r)/delta  {Resulting color is between cyan and yellow}
      else if b = max then
        h := 4 + (r - g)/delta; {Resulting color is between magenta and cyan}
      h := h * 60               {Convert hue to degrees}
      if h < 0 then
        h := h + 360            {Make sure hue is nonnegative}
    end {Chromatic case}
end {RGB_To_HSV}
```

Fig. 13.33 Algorithm for converting from RGB to HSV color space.

its main diagonal, is like the hexagon in Fig. 13.31, except smaller. Each plane of constant V in HSV space corresponds to such a view of a subcube in RGB space. The main diagonal of RGB space becomes the V axis of HSV space. Thus, we can see intuitively the correspondence between RGB and HSV. The algorithms of Figs. 13.33 and 13.34 define the correspondence precisely by providing conversions from one model to the other.

13.3.5 The HLS Color Model

The HLS (hue, lightness, saturation) color model is defined in the double-hexcone subset of a cylindrical space, as seen in Fig. 13.35. Hue is the angle around the vertical axis of the double hexcone, with red at 0° (some discussions of HLS have blue at 0°; we place red at 0° for consistency with the HSV model). The colors occur around the perimeter in the same order as in the CIE diagram when its boundary is traversed counterclockwise: red, yellow, green, cyan, blue, and magenta. This is also the same order as in the HSV single-hexcone model. In fact, we can think of HLS as a deformation of HSV, in which white is pulled

```
procedure HSV_To_RGB (var r, g, b: real; h, s, v : real);
{Given: h in [0,360] or UNDEFINED, s and v in [0,1].
 Desired: r, g, b, each in [0,1].}
begin
  if s = 0 then                        {The color is on the black-and-white center line.}
    if h = UNDEFINED then              {Achromatic color: There is no hue.}
      begin                            {This is the achromatic case.}
        r := v;
        g := v;
        b := v
      end
    else Error                         {By our convention, error if s = 0 and h has a value.}
  else                                 {Chromatic color: s ≠ 0, so there is a hue.}
    begin                              {This is the chromatic case.}
      if h = 360 then                  {360° is equivalent to 0°.}
        h := 0;
      h := h/60;                       {h is now in [0,6).}
      i := Floor (h);                  {Floor returns the largest integer <= h}
      f := h – i;                      {f is the fractional part of h.}
      p := v * (1 – s);
      q := v * (1 – (s * f));
      t := v * (1 – (s * (1 – f))
      case i of
        0: (r, g, b) := (v, t, p);     {Shorthand Pascal for triplet assignment}
        1: (r, g, b) := (q, v, p);
        2: (r, g, b) := (p, v, t);
        3: (r, g, b) := (p, q, v);
        4: (r, g, b) := (t, p, v);
        5: (r, g, b) := (v, p, q)
      end {case}
    end {Chromatic case}
end {HSV_To_RGB}
```

Fig. 13.34 Algorithm for converting from HSV to RGB color space.

upward to form the upper hexcone from the $V = 1$ plane. As with the single-hexcone model, the complement of any hue is located 180° farther around the double hexcone, and saturation is measured radially from the vertical axis, from 0 on the axis to 1 on the surface. Lightness is 0 for black (at the lower tip of the double hexcone) to 1 for white (at the upper tip). Color Plate II.9 shows a view of the HLS model. Again, the terms hue, lightness, and saturation in this model are similar to, but are not exactly identical to, the same terms as they were introduced in an earlier section. Color Plate II.10 shows a different view of the space.

The procedures of Figs. 13.36 and 13.37 perform the conversions between HLS and RGB. They are modified from those given by Metrick [GSPC79] to leave H UNDEFINED when $S = 0$, and to have $H = 0$ for red rather than for blue.

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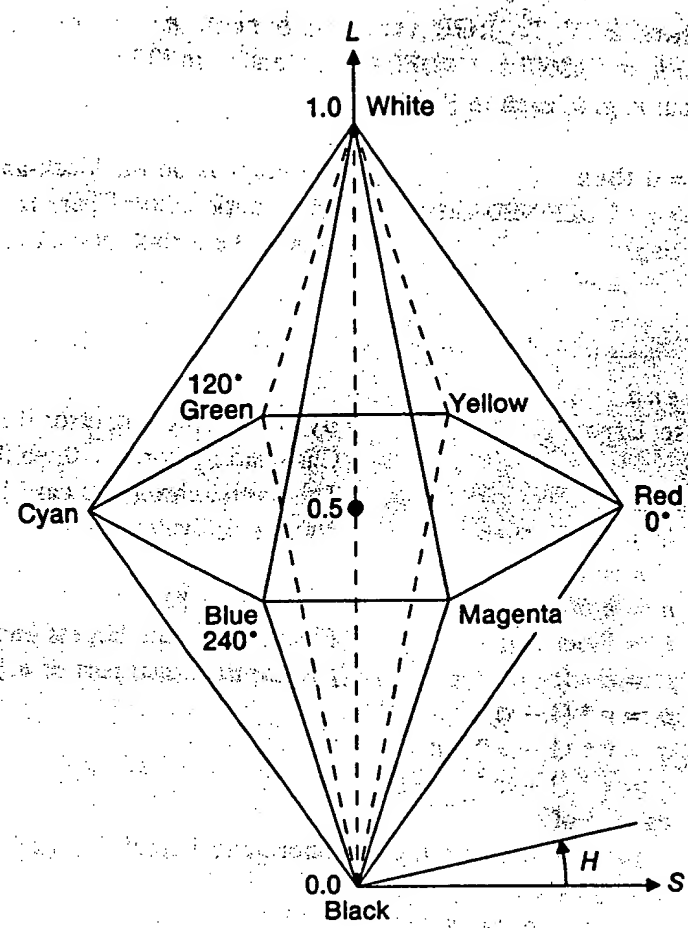

Fig. 13.35 Double-hexcone HLS color model.

The HLS model, like the HSV model, is easy to use. The grays all have $S = 0$, but the maximally saturated hues are at $S = 1$, $L = 0.5$. If potentiometers are used to specify the color-model parameters, the fact that L must be 0.5 to get the strongest possible colors is a disadvantage over the HSV model, in which $S = 1$ and $V = 1$ achieve the same effect. However, analogously to HSV, the colors of the $L = 0.5$ plane are *not* all of the same perceived brightness. Hence two different colors of equal perceived brightness will generally have different values of L. Furthermore, neither HLS nor any of the other models discussed thus far in this section are perceptually uniform, in the sense discussed in Section 13.2.

The recently developed Tektronix TekHVC (hue, value, chroma) color system, a modification of the CIE LUV perceptually uniform color space discussed in Section 13.2, does provide a color space in which measured and perceived distances between colors are approximately equal. This is an important advantage of both the CIE LUV and TekHVC models. Figure 13.38 shows one view of the HVC color model, and Color Plate II.11 shows another view. Details of the transformations from CIE to TekHVC have not been released. However, we see from Eq. (13.22) that the transformation from CIE XYZ to CIE LUV is computationally straightforward, with the cube root being the most computationally intense element. Thus, we expect that perceptually uniform color spaces will come to be more widely used in the future.

```
procedure RGB_To_HLS (r, g, b: real; var h, l, s: real);
{Given: r, g, b each in [0, 1].
 Desired: h in [0,360), l and s in [0, 1], except if s = 0, then h = UNDEFINED.}
begin
  max := Maximum (r, g, b);
  min := Minimum (r, g, b);
  l := (max + min)/2            {This is the lightness}
  {Next calculate saturation}
  if max = min then
    begin {Achromatic case, because r = g = b}
      s := 0;
      h := UNDEFINED
    end {Achromatic case}
  else
    begin {Chromatic case}
      {First calculate the saturation.}
      if l <= 0.5 then
        s := (max - min)/(max + min)
      else s := (max - min)/(2 - max - min);
      {Next calculate the hue.}
      delta := max - min
      if r = max then
        h := (g - b)/delta          {Resulting color is between yellow and magenta}
      else if g = max then
        h := 2 + (b - r)/delta      {Resulting color is between cyan and yellow}
      else if b = max then
        h := 4 + (r - g)/delta;     {Resulting color is between magenta and cyan}
      h := h * 60                   {Convert to degrees}
      if h < 0.0 then
        h := h + 360                {Make degrees be nonnegative}
    end {Chromatic case}
end {RGB_To_HLS}
```

Fig. 13.36 Algorithm for converting from RGB to HLS color space.

13.3.6 Interactive Specification of Color

Many application programs allow the user to specify colors of areas, lines, text, and so on. If only a small set of colors is provided, menu selection from samples of the available colors is appropriate. But what if the set of colors is larger than can reasonably be displayed in a menu?

The basic choices are to use English-language names, to specify the numeric coordinates of the color in a color space (either by typing or with slider dials), or to interact directly with a visual representation of the color space. Naming is in general unsatisfactory because it is ambiguous and subjective ("a light navy blue with a touch of green"), and it is also the antithesis of graphic interaction. On the other hand, [BERK82] describes CNS, a fairly well-defined color-naming scheme that uses terms such as "greenish-yellow," "green-yellow," and "yellowish-green" to distinguish three hues between green and

```
procedure HLS_To_RGB (var r, g, b: real; h, l, s: real);
{Given: h in [0,360] or UNDEFINED, l and s in [0,1].
 Desired: r, g, b, each in [0,1]}
function Value (n1, n2, hue: real)
  begin
    if hue > 360 then
      hue := hue - 360
    else if hue < 0 then
      hue :=hue + 360
    if hue < 60 then
      Value := n1 + (n2 - n1) * hue/60
    else if hue < 180 then
      Value := n2
    else if hue < 240 then
      Value :=n1 + (n2 -n1) * (240 - hue)/60
    else Value := n1
  end {Value}
begin
  if l <= 0.5 then
    m2 := l * (1 + s )
  else
    m2 := l + s - l * s;
  m1 := 2 * l - m2
  if s = 0 then                    {Achromatic: There is no hue.}
    if h = UNDEFINED then
      r := g := b := l             {This is the achromatic case.}
    else ERROR                     {Error if s = 0 and h has a value}
  else                             {Chromatic case, so there is a hue}
    begin
      r := Value (m1, m2, h + 120);
      g := Value (m1, m2, h);
      b := Value (m1, m2, h - 120)
    end
end {HLS_To_RGB}
```

Fig. 13.37 Algorithm for converting from HLS to RGB color space.

yellow. In an experiment, users of CNS were able to specify colors more precisely than were users who entered numeric coordinates in either RGB or HSV space.

Coordinate specification can be done with slider dials, as in Fig. 13.39, using any of the color models. If the user understands how each dimension affects the color, this technique works well. Probably the best interactive specification method is to let the user interact directly with a representation of the color space, as shown in Fig. 13.40. The line on the circle (representing the $V = 1$ plane) can be dragged around to determine which slice of the HSV volume is displayed in the triangle. The cursor on the triangle can be moved around to specify saturation and value. As the line or the cursor is moved, the numeric readouts change value. When the user types new values directly into the numeric readouts, the line and cursor are repositioned. The color sample box shows the currently selected

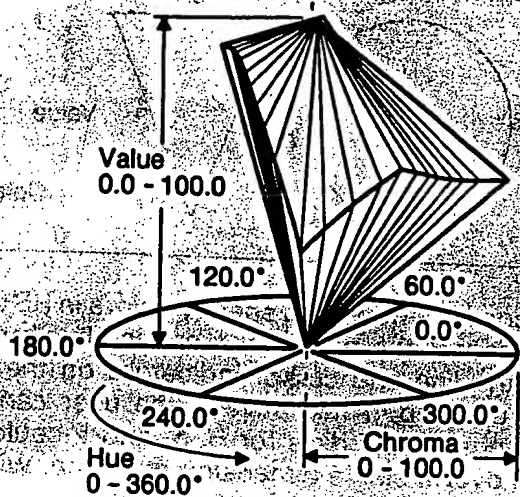

Fig. 13.38 The TekHVC color model. (Courtesy of Tektronix, Inc.)

color. Color Plate II.12 shows a similar method used for the HSV model.

[SCHW87] describes color-matching experiments in which subjects used a data tablet to specify colors in several models including RGB, YIQ, LAB [WYSZ82], and HSV. HSV was found to be slow but accurate, whereas RGB was faster but less accurate. There is a widespread belief that the HSV model is especially tractable, usually making it the model of choice.

Many interactive systems that permit user specification of color show the user the current color settings as a series of adjacent patches of color, as in part (a) of Fig. 13.39, or as the color of the single pixel value currently being set, as in part (b). As the user

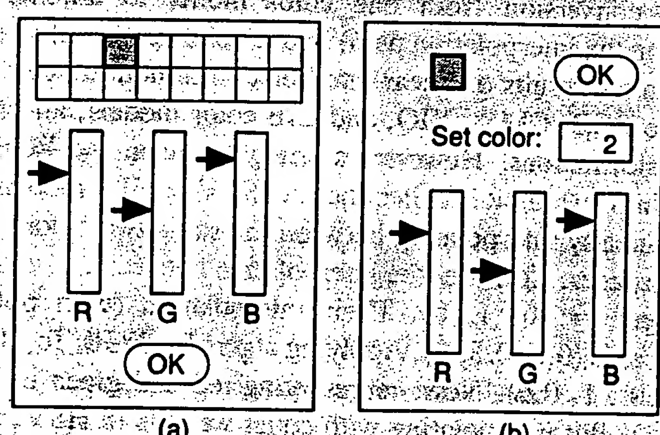

Fig. 13.39 Two common ways of setting colors. In (a), the user selects one of 16 colors to set; the selected color is designated with the thick border. The RGB slider dials control the color; OK is selected to dismiss the color control panel. In (b), the number of the color to be set is typed, and the current color is displayed in the gray-toned box. In both cases, the user must simultaneously see the actual display in order to understand the effects of the color change.

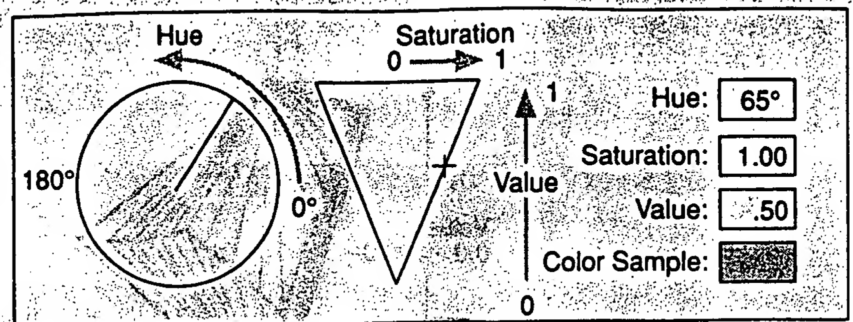

Fig. 13.40 A convenient way to specify colors in HSV space. Saturation and value are shown by the cursor in the triangular area, and hue by the line in the circular area. The user can move the line and cursor indicators on the diagrams, causing the numeric readouts to be updated. Alternatively, the user can type new values, causing the indicators to change. Slider dials for *H*, *S*, and *V* could also be added, giving the user accurate control over a single dimension at a time, without the need to type values.

manipulates the slider dials, the color sample changes. However, a person's perception of color is affected by surrounding colors and the sizes of colored areas, as shown in Color Plate II.13; hence, the color as perceived in the feedback area will probably differ from the color as perceived in the actual display. It is thus important that the user also see the actual display while the colors are being set.

13.3.7 Interpolating in Color Space

Color interpolation is necessary in at least three situations: for Gouraud shading (Section 16.2.4), for antialiasing (Section 3.17), and in blending two images together as for a fade-in, fade-out sequence. The results of the interpolation depend on the color model in which the colors are interpolated; thus, care must be taken to select an appropriate model.

If the conversion from one color model to another transforms a straight line (representing the interpolation path) in one color model into a straight line in the other color model, then the results of linear interpolation in both models will be the same. This is the case for the RGB, CMY, YIQ, and CIE color models, all of which are related by simple affine transformations. However, a straight line in the RGB model does *not* in general transform into a straight line in either the HSV or HLS models. Color Plate II.14 shows the results of linearly interpolating between the same two colors in the HSV, HSL, RGB, and YIQ color spaces. Consider the interpolation between red and green. In RGB, red = (1, 0, 0) and green = (0, 1, 0). Their interpolation (with both weights equal to 0.5 for convenience) is (0.5, 0.5, 0). Applying algorithm RGB_To_HSV (Fig. 13.33) to this result, we have (60°, 1, 0.5). Now, representing red and green in HSV, we have (0°, 1, 1) and (120°, 1, 1). But interpolating with equal weights in HSV, we have (60°, 1, 1); thus, the value differs by 0.5 from the same interpolation in RGB.

As a second example, consider interpolating red and cyan in the RGB and HSV models. In RGB, we start with (1, 0, 0) and (0, 1, 1), respectively, and interpolate to (0.5, 0.5, 0.5), which in HSV is represented as (UNDEFINED, 0, 0.5). In HSV, red and cyan are (0°, 1, 1) and (180°, 1, 1). Interpolating, we have (90°, 1, 1); a new hue at maximum value and saturation has been introduced, whereas the "right" result of combining equal amounts

of complementary colors is a gray value. Here, again, interpolating and then transforming gives different results from transforming and then interpolating.

For Gouraud shading, any of the models can be used, because the two interpolants are generally so close together that the interpolation paths between the colors are close together as well. When two images are blended—as in a fade-in, fade-out sequence or for antialiasing—the colors may be quite distant, and an additive model, such as RGB, is appropriate. If, on the other hand, the objective is to interpolate between two colors of fixed hue (or saturation) and to maintain the fixed hue (or saturation) for all interpolated colors, then HSV or HLS is preferable. But note that a fixed-saturation interpolation in HSV or HLS is *not* seen as having exactly fixed saturation by the viewer [WARE87].

13.4 REPRODUCING COLOR

Color images are reproduced in print in a way similar to that used for monochrome images, but four sets of halftone dots are printed, one for each of the subtractive primaries, and another for black. In a process called *undercolor removal*, black replaces equal amounts of cyan, magenta, and yellow. This creates a darker black than is possible by mixing the three primaries, and hastens drying by decreasing the amounts of cyan, magenta, and yellow ink needed. The orientation of each of the grids of dots is different, so that interference patterns are not created. Color Plate II.15 shows an enlarged halftone color pattern. Our eyes spatially integrate the light reflected from adjacent dots, so that we see the color defined by the proportions of primaries in adjacent dots. This spatial integration of different colors is the same phenomenon we experience when viewing the triads of red, green, and blue dots on a color monitor.

We infer, then, that color reproduction in print and on CRTs depends on the same spatial integration used in monochrome reproduction. The monochrome dithering techniques discussed in Section 13.1.2 can also be used with color to extend the number of available colors, again at the expense of resolution. Consider a color display with 3 bits per pixel, one each for red, green, and blue. We can use a 2×2 pixel pattern area to obtain 125 different colors: each pattern can display five intensities for each of red, green, and blue, by using the halftone patterns in Fig. 13.8. This results in $5 \times 5 \times 5 = 125$ color combinations.

Not all color reproduction depends exclusively on spatial integration. For instance, xerographic color copiers, ink-jet plotters, and thermal color printers actually mix subtractive pigments on the paper's surface to obtain a small set of different colors. In xerography, the colored pigments are first deposited in three successive steps, then are heated and melted together. The inks sprayed by the plotter mix before drying. Spatial integration may be used to expand the color range further.

A related quantization problem occurs when a color image with n bits per pixel is to be displayed on a display of $m < n$ bits per pixel with no loss of spatial resolution. Here, color resolution *must* be sacrificed. In this situation, there are two key questions: Which 2^m colors should be displayed? What is the mapping from the set of 2^n colors in the image to the smaller set of 2^m colors being displayed?

The simple answers are to use a predefined set of display colors and a fixed mapping from image colors to display colors. For instance, with $m = 8$, a typical assignment is 3 bits

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to red and green and 2 to blue (because of the eye's lower sensitivity to blue). Thus, the 256 displayable colors are all the combinations of eight reds, eight greens, and four blues. The specific values for the red, green, and blue colors would be spaced across the range of 0.0 to 1.0 range on a ratio scale, as discussed in Section 13.1.1. For an image with 6 bits per color and hence 64 levels for each color, the 64 red colors are mapped into one of the eight displayable reds, and similarly for the greens. The 64 blue colors are mapped into just four blues.

With this solution, however, if all the blue image colors are clustered together in color space, they might all be displayed as the same blue, whereas the other three displayable blues might go unused. An adaptive scheme would take this possibility into account and would divide up the blue-value range on the basis of the distribution of values in the range. Heckbert [HECK82] describes two approaches of this type: the popularity algorithm and the median-cut algorithm.

The *popularity algorithm* creates a histogram of the image's colors, and uses the 2^m most frequent colors in the mapping. The *median-cut algorithm* recursively fits a box around the colors used in the image, splitting the box along its longer dimension at the median in that dimension. The recursion ends when 2^m boxes have been created; the centroid of each box is used as the display color for all image colors in the box. The median-cut algorithm is slower than is the popularity algorithm, but produces better results. Another way of splitting the boxes is described in [WAN88].

Creating an *accurate* color reproduction is much more difficult than is approximating colors. Two display monitors can be calibrated to create the same tristimulus values; the multistep process is described in detail in [COWA83; MEYE83]. The steps are to measure the chromaticity coordinates of the monitor phosphors, then to adjust the brightness and contrast controls of each of the monitor guns so that the same white chromaticity is produced whenever $R = G = B$, and to determine the appropriate gamma correction for each gun.

Making slides or movie film that look exactly like the image on a display is difficult, because many variables are involved. They include the gamma correction of the display and of the CRT used in the film recorder; the color of light emitted by the CRT in the film recorder; the filters used in the film recorder; the type of film used; the quality and temperature of the developing chemicals, the length of time the film is in the chemicals, and the color of light emitted by the bulb in the slide or film projector. Fortunately, all these variables can be quantified and controlled, albeit with considerable difficulty.

Controlling the color match on printed materials is also difficult; the printing process, with its cyan, magenta, yellow, and black primaries, requires careful quality control to maintain registration and ink flow. The paper texture, absorbancy, and gloss also affect the result. Complicating matters further, the simple subtractive CMY color model discussed in Section 13.3.2 cannot be used directly, because it does not take into account these complications of the printing process. More detail can be found in [STON88].

Even if extreme care is taken in color reproduction, the results may not seem to match the original. Lighting conditions and reflections from the display can cause colors with the same measured chromaticity coordinates to appear to be different. Fortunately, the purpose of the reproduction is usually (although not always) to maintain color relationships between different parts of the image, rather than to make an exact copy.

13.5 USING COLOR IN COMPUTER GRAPHICS

We use color for aesthetics, to establish a tone or mood, for realism, as a highlight, to identify associated areas as being associated, and for coding. With care, color can be used effectively for these purposes. In addition, users tend to like color, even when there is no quantitative evidence that it helps their performance. Although cost-conscious buyers may scoff at color monitors, we believe that anything that encourages people to use computers is important!

Careless use of color can make the display less useful or less attractive than a corresponding monochrome presentation. In one experiment, introduction of meaningless color reduced user performance to about one-third of what it was without color [KREB79]. Color should be employed conservatively. Any decorative use of color should be subservient to the functional use, so that the color cannot be misinterpreted as having some underlying meaning. Thus, the use of color, like all other aspects of a user–computer interface, must be tested with real users to identify and remedy problems. Of course, some individuals may have other preferences, so it is common practice to provide defaults chosen on the basis of color usage rules, with some means for the user to change the defaults. A conservative approach to color selection is to design first for a monochrome display, to ensure that color use is purely redundant. This avoids creating problems for color-deficient users and also means that the application can be used on a monochrome display. Additional information on color deficiencies is given in [MEYE88]. The color choices used in the window managers shown in Color Plates I.26 through I.29 are quite conservative. Color is not used as a unique code for button status, selected menu item, and so forth.

Many books have been written on the use of color for aesthetic purposes, including [BIRR61]; we state here just a few of the simpler rules that help to produce color harmony. The most fundamental rule of color aesthetics is to select colors according to some method, typically by traversing a smooth path in a color model or by restricting the colors to planes or hexcones in a color space. This might mean using colors of constant lightness or value. Furthermore, colors are best spaced at equal *perceptual* distances (this is not the same as being at equally spaced increments of a coordinate, and can be difficult to implement). Recall too that linear interpolation (as in Gouraud shading) between two colors produces different results in different color spaces (see Exercise 13.10 and Color Plate II.14).

A random selection of different hues and saturations is usually quite garish. Alvy Ray Smith performed an informal experiment in which a 16×16 grid was filled with randomly generated colors. Not unexpectedly, the grid was unattractive. Sorting the 256 colors according to their H, S, and V values and redisplaying them on the grid in their new order improved the appearance of the grid remarkably.

More specific instances of these rules suggest that, if a chart contains just a few colors, the complement of one of the colors should be used as the background. A neutral (gray) background should be used for an image containing many different colors, since it is both harmonious and inconspicuous. If two adjoining colors are not particularly harmonious, a thin black border can be used to set them apart. This use of borders is also more effective for the achromatic (black/white) visual channel, since shape detection is facilitated by the black outline. Some of these rules are encoded in ACE (A Color Expert), an expert system for selecting user-interface colors [MEIE88]. In general, it is good to minimize the number of

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different colors being used (except for shading of realistic images).

Color can be used for coding, as discussed in Chapter 9 and illustrated by Color Plate II.16. However, several cautions are in order. First, color codes can easily carry unintended meanings. Displaying the earnings of company A as red and those of company B as green might well suggest that company A is in financial trouble, because of our learned associations of colors with meanings. Bright, saturated colors stand out more strongly than do dimmer, paler colors, and may give unintended emphasis. Two elements of a display that have the same color may be seen as related by the same color code, even if they are not. This problem often arises when color is used both to group menu items and to distinguish display elements, such as different layers of a printed circuit board or VLSI chip; for example, green display elements tend to be associated with menu items of the same color. This is one of the reasons that use of color in user-interface elements, such as menus, dialogue boxes, and window borders, should be restrained. (Another reason is to leave as many colors as possible free for the application program itself.)

A number of color usage rules are based on physiological rather than aesthetic considerations. For example, because the eye is more sensitive to spatial variation in intensity than it is to variation in chromaticity, lines, text, and other fine detail should vary from the background not just in chromaticity, but in brightness (perceived intensity) as well—especially for colors containing blue, since relatively few cones are sensitive to blue. Thus, the edge between two equal-brightness colored areas that differ only in the amount of blue will be fuzzy. On the other hand, blue-sensitive cones spread out farther on the retina than do red- and green-sensitive ones, so our peripheral color vision is better for blue (this is why many police-car flashers are now blue instead of red).

Blue and black differ very little in brightness, and are thus a particularly bad combination. Similarly, yellow on white is relatively hard to distinguish, because both colors are quite bright (see Exercise 13.11). Color plates I.28 and I.29 show a very effective use of yellow to highlight black text on a white background. The yellow contrasts very well with the black text and also stands out. In addition, the yellow highlight is not as overpowering as a black highlight with reversed text (that is, with the highlighted text in white on a black highlight), as is common on monochrome displays.

White text on a blue background provides a good contrast that is less harsh than white on black. It is good to avoid reds and greens with low saturation and luminance, as these are the colors confused by those of us who are red–green color blind, the most common form of color-perception deficiency. Meyer and Greenberg describe effective ways to choose colors for color-blind viewers [MEYE88].

The eye cannot distinguish the color of very small objects, as already remarked in connection with the YIQ NTSC color model, so color coding should not be applied to small objects. In particular, judging the color of objects subtending less than 20 to 40 minutes of arc is error-prone [BISH60, HAEU76]. An object 0.1 inches high, viewed from 24 inches (a typical viewing distance) subtends this much arc, which corresponds to about 7 pixels of height on a 1024-line display with a vertical height of 15 inches. It is clear that the color of a single pixel is quite difficult to discern (see Exercise 13.18).

The perceived color of a colored area is affected by the color of the surrounding area, as is very evident in Color Plate II.13; this effect is particularly problematic if colors are used to encode information. The effect is minimized when the surrounding areas are some shade of gray or are relatively unsaturated colors.

The color of an area can actually affect its perceived size. Cleveland and McGill discovered that a red square is perceived as larger than is a green square of equal size [CLEV83]. This effect could well cause the viewer to attach more importance to the red square than to the green ones.

If a user stares at a large area of highly saturated color for several seconds and then looks elsewhere, an afterimage of the large area will appear. This effect is disconcerting, and causes eye strain. Use of large areas of saturated colors is hence unwise. Also, large areas of different colors can appear to be at different distances from the viewer, because the index of refraction of light depends on wavelength. The eye changes its focus as the viewer's gaze moves from one colored area to another, and this change in focus gives the impression of differing depths. Red and blue, which are at opposite ends of the spectrum, have the strongest depth-disparity effect, with red appearing closer and blue more distant. Hence, simultaneously using blue for foreground objects and red for the background is unwise; the converse is fine.

With all these perils and pitfalls of color usage, is it surprising that one of our first-stated rules was to apply color conservatively?

13.6 SUMMARY

The importance of color in computer graphics will continue to increase as color monitors and color hardcopy devices become the norm in many applications. In this chapter, we have introduced those color concepts most relevant to computer graphics; for more information, see the vast literature on color, such as [BILL81; BOYN79; GREG66; HUNT87; JUDD75; WYSZ82]. More background on artistic and aesthetic issues in the use of color in computer graphics can be found in [FROM84; MARC82; MEIE88; MURC85]. The difficult problems of precisely calibrating monitors and matching the colors appearing on monitors with printed colors are discussed in [COWA83; STON88].

EXERCISES

13.1 Derive an equation for the number of intensities that can be represented by $m \times m$ pixel patterns, where each pixel has w bits.

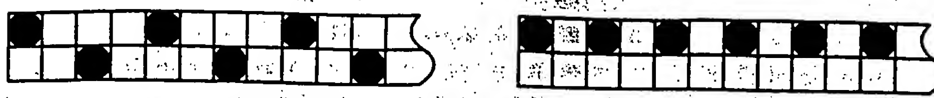
13.2 Write the programs needed to gamma-correct a black-and-white display through a look-up table. Input parameters are γ, I_0, m, the number of intensities desired, and K, the constant in Eq. (13.5).

13.3 Write an algorithm to display a pixel array on a bilevel output device. The inputs to the algorithm are an $m \times m$ array of pixel intensities, with w bits per pixel, and an $n \times n$ growth sequence matrix. Assume that the output device has resolution of $m \cdot n \times m \cdot n$.

13.4 Repeat Exercise 13.3 by using ordered dither. Now the output device has resolution $m \times m$, the same as the input array of pixel intensities.

13.5 Write an algorithm to display a filled polygon on a bilevel device by using an $n \times n$ filling pattern.

13.6 When certain patterns are used to fill a polygon being displayed on an interlaced raster display, all of the "on" bits fall on either the odd or the even scan lines, introducing a slight amount of flicker. Revise the algorithm from Exercise 13.5 to permute rows of the $n \times n$ pattern so that alternate



(a) (b)

Fig. 13.41 Results obtained by using intensity level 1 from Fig. 13.8 in two ways: (a) with alternation (intensified pixels are on both scan lines), and (b) without alternation (all intensified pixels are on the same scan line).

replications of the pattern will alternate use of the odd and even scan lines. Figure 13.41 shows the results obtained by using intensity level 1 from Fig. 13.8, with and without this alternation.

13.7 Given a spectral energy distribution, how would you find the dominant wavelength, excitation purity, and luminance of the color it represents?

13.8 Plot the locus of points of the constant luminance values 0.25, 0.50, and 0.75, defined by $Y = 0.30R + 0.59G + 0.11B$, on the RGB cube, the HLS double hexcone, and the HSV hexcone.

13.9 Why are the opposite ends of the spectrum in the CIE diagram connected by a *straight* line?

13.10 Express, in terms of R, G, and B: the I of YIQ, the V of HSV, and the L of HSL. Note that I, V, and L are not the same.

13.11 Calculate in YIQ color space the luminances of the additive and subtractive primaries. Rank the primaries by luminance. This ranking gives their relative intensities, both as displayed on a black-and-white television and as perceived by our eyes.

13.12 Discuss the design of a raster display that uses HSV or HLS, instead of RGB, as its color specification.

13.13 In which color models are the rules of color harmony most easily applied?

13.14 Verify that Eq. (13.27) can be rewritten as Eq. (13.29) when $R = G = B = 1$.

13.15 If the white color used to calculate C_r, C_g, and C_b in Eq. (13.29) is given by x_w, y_w, and Y_w rather than by X_w, Y_w, and Z_w, what are the algebraic expressions for C_r, C_g, and C_b?

13.16 Rewrite the HSV-to-RGB conversion algorithm to make it more efficient. Replace the assignment statements for p, q, and t with: $vs := v * s$; $vsf := vs * f$; $p := v - vs$; $q := v - vsf$; $t := p + vsf$. Also assume that R, G, and B are in the interval [0, 255], and see how many of the computations can be converted to integer.

13.17 Write a program that displays, side by side, two 16×16 grids. Fill each grid with colors. The left grid will have 256 colors randomly selected from HSV color space (created by using a random-number generator to choose one out of 10 equally spaced values for each of H, S, and V). The right grid contains the same 256 colors, sorted on H, S, and V. Experiment with the results obtained by varying which of H, S, and V is used as the primary sort key.

13.18 Write a program to display on a gray background small squares colored orange, red, green, blue, cyan, magenta, and yellow. Each square is separated from the others and is of size $n \times n$ pixels, where n is an input variable. How large must n be so that the colors of each square can be unambiguously judged from distances of 24 and of 48 inches? What should be the relation between the two values of n? What effect, if any, do different background colors have on this result?

13.19 Calculate the number of bits of look-up–table accuracy needed to store 256 different intensity levels given dynamic intensity ranges of 50, 100, and 200.

13.20 Write a program to interpolate linearly between two colors in RGB, HSV, and HSL. Accept the two colors as input, allowing them to be specified in any of these three models.